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Spatial-Spectral Volume Holographic Systems: resolution dependence on effective thickness

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The resolution dependence of spatial-spectral volume holographic imaging systems on angular and spectral bandwidth of non-uniform gratings is investigated. Modeling techniques include a combination of the approximate coupled wave analysis and transfer matrix methods for holograms recorded in absorptive medium. The effective thickness of the holograms is used as an estimator of the resolution of the imaging systems. The methodology presented here assists in the design and optimization of volume holographic Simulation results based on our approach are confirmed with experiments and show proof of consistency and usefulness of the proposed models.

1. Introduction

Three-dimensional (3D) imaging instruments are essential tools in the biological and medical sciences [1]. During the last decade, several volume holographic imaging systems have been proposed to provide this functionality [3-8]. Among them, the spatial-spectral volume holographic imaging system (S^2 -VHIS) [5-8] can produce multiple-depth images without requiring mechanical scanning. S^2 -VHIS utilizes high angular and spectral selectivity of volume holograms to connect the entrance and exit pupils of the S^2 -VHIS through light paths defined by the Bragg phase matching condition [5-8]. By using several multiplexed holograms, each one constructed with a waverfront matched to a specific depth, several depths in object space can be imaged simultaneously to different location on the camera. S^2 -VHIS prototypes [5-8] have been demonstrated using 1,9-phenanthrenequinone-doped poly-(methylmethacrylate) (PQ-PMMA) holographic recording medium [9] obtaining lateral spatial resolutions as high as 3 μ m [6-8].

Current S^2 -VHIS prototypes have unequal resolution between the horizontal and vertical axes. This is because imaging along the horizontal axis depends on the angular and spectral bandwidth of the hologram while resolution along the vertical axis does not depend on the hologram.

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In this paper the dependence of the S^2 -VHIS resolution on the angular and spectral bandwidth properties of non-uniform holograms is investigated. The modeling techniques used are a combination of the approximate coupled wave analysis (ACWA) [12-14] and transfer matrix methods for holograms recorded in absorptive medium [15-17]. The usefulness of the concept of effective thickness for predicting grating selectivity is evaluated [18-20]. The comprehensive methodology presented here assists in the design and optimization of non-uniform gratings for applications to S^2 -VHIS.

The remainder of this paper is divided into five sections. In the second section, the operation of the S^2 -VHIS is described. In section 3, different modeling techniques for volume holograms with uniform and non-uniform index modulation profiles are reviewed. In section 4, the S^2 -VHIS resolution dependence on the hologram's performance is derived. Modeling and experimental validation are presented in section 5. The last section summarizes the result of this analysis and outline future work.

2. Basic operation of S^2 -VHIS

The basic configuration of a S^2 -VHIS consists of a 4F imaging system with a holographic element placed in the Fourier plane [2-8]. The holographic element is composed of thick angle-multiplexed planar and spherical wave gratings with high angular and spectral selectivity.

For a specific wavelength, each grating will select only a specific wavefront that originates at a particular depth from within the scattering object to the desired location on the image plane. Multiplexing several gratings into the same volume of recording material allows points at different depths in object space to be mapped simultaneously to non-overlapping locations in the image plane.

The layout depicted in Figure 1 serves as an example of the S^2 -VHIS operation. For each plane in object space, a mapping is produced by two properties of volume holograms [13,14] the spatial degeneracy and the angular dispersion. Due to the first property, the wavefront of a point source at any position along the y-axis (vertical in Fig. 1) satisfies the Bragg phase matching condition of the holographic optical element (HOE) and therefore is diffracted to the collector lens. The field of view (FOV) in the vertical direction is simply specified by the FOV of the lens train used in the system.

The cylinders in Fig. 1 are utilized for explanation purposes; the shape of the FOV is not a straight line as represented by the cylinder axis but a curved line as explained in [21-22]. The resolution in the y-axis is not affected by the dispersive properties of the holograms but is dependent on the objective lens and other optical elements of the S^2 -VHIS.

The angular selectivity of the hologram and the spectral bandwidth of the source define the FOV along the x-axis. This FOV is represented by several cylinders along the x-axis. Each cylinder has a different gray level intensity which indicates that it results from a different wavelength. The resolution in this axis depends on the spectral properties of the hologram. The FOV along this axis depends on the spectral bandwidth of the read-out source. Current prototypes utilize LEDs with Full Width Half Maximum (FWHM) bandwidth ranging from 20 to 50 nm.

Currently, S^2 -VHIS prototypes have been demonstrated using a recording medium consisting of 1,9-phenanthrenquinone- (PQ-) doped poly-(methyl methacrylate) (PMMA) with geometrical thickness ranging from 1 to 3 mm. This recording medium has been selected for the VHIS due to its capabilities of producing highly selective gratings with high diffraction efficiency [9-11].

3. Modeling Techniques for Volume Holograms

Modeling techniques to evaluate the performance volume holograms include the Born approximation [2-5], approximate coupled wave analysis (ACWA) [12-14] and rigorous coupled wave analysis, RCWA [23-24]. The Born approximation [2-5] provides a simplified analytical model for volume holographic gratings. However, this method assumes weak interaction between the incident and diffracted beam. This is not the case for the holograms used in current prototypes of the S²-VHIS [7-8,22].

The RCWA provides the most accurate analysis of diffraction phenomena in holographic elements with arbitrary reconstruction conditions. However, for this type of hologram, RCWA is too computationally intensive to be practical for system design and optimization.

An approximate coupled wave algorithm (ACWA) can provide an accurate and fast estimation of diffraction efficiencies and has been experimentally validated for the S²-VHIS in reference [8]. Moreover, the analytical expression of ACWA provides a more intuitive description of the diffraction phenomena that is helpful in the investigation on the resolution limitations in the S²-VHIS.

In ACWA, there are two fundamental parameters that describe the diffraction process: the strength and direction of the diffracted beam. The direction of the diffracted beam is represented as a vector inside the grating and is obtained from the phase matching conditions [12-14,23-24]

$$\begin{aligned}\vec{u}^{(d)} &= (u_x^{(i)} - K_x)\vec{x} + (u_y^{(i)} - K_y)\vec{y} + u_z^{(d)}\vec{z} \\ \vec{u}^{(d)} &= u_x^{(d)}\vec{x} + u_y^{(d)}\vec{y} + u_z^{(d)}\vec{z},\end{aligned}\quad (1)$$

where $\vec{u}^{(i)}$ is the incident propagation vector inside the medium, $\vec{u}^{(d)}$ is the diffracted propagation vector inside the medium, n_2 is the refractive index of the grating material,

$$\begin{aligned}u_z^{(d)} &= \sqrt{k_2^2 - |u_x^{(d)}|^2 - |u_y^{(d)}|^2}, \\ k_2 &= \frac{2\pi n_2}{\lambda},\end{aligned}\quad (2)$$

λ is the free-space wavelength, n_2 is the refractive index of the medium, and

$\vec{K} = K_x\vec{x} + K_y\vec{y} + K_z\vec{z}$ is the grating vector. The grating vector is given by

$$\vec{K} = \frac{2\pi n_2}{\lambda_c} [\vec{r}^{<m>} - \vec{s}^{<m>}], \quad (3)$$

where λ_c is the grating construction wavelength, and $\vec{r}^{<m>}$ and $\vec{s}^{<m>}$ are the construction reference and signal beam vectors inside the recording medium [12-15]. For simplicity and without significant loss of generality it is assumed that $K_y = 0$.

For a transmission grating, the 2D representation of the diffraction efficiency (DE) for a TE wave is given by [12-14],

$$DE(\theta, \lambda) = \frac{\sin^2 \left(\sqrt{v(\theta, \lambda)^2 + \xi(\theta, \lambda)^2} \right)}{1 + \left(\frac{\xi(\theta, \lambda)}{v(\theta, \lambda)} \right)^2} \quad (4)$$

where v is a function that determines the maximum diffraction efficiency of the grating for a specific reconstruction wavelength and angle, and ξ indicates the variation of the reconstruction parameters from the Bragg condition. For a lossless transmission grating the functional form of these parameters are given by,

$$v(\theta, \lambda) = \frac{\pi \Delta n t_H}{\lambda \sqrt{c_r(\theta) c_s(\theta)}}, \quad (5)$$

$$\vartheta(\theta, \lambda) = K \cos(\phi - \theta) - \frac{K^2}{4\pi n_2} \lambda, \quad (6)$$

$$\xi(\theta, \lambda) = \frac{\vartheta(\theta, \lambda) t_H}{2c_s(\theta)}, \quad (7)$$

where Δn and t_H are the index modulation and the thickness of the hologram respectively,

$\vartheta(\theta, \lambda)$ is the detuning parameter, $c_s(\theta) = \cos(\theta)$, $c_r(\theta) = \cos(\theta) - \frac{K_z}{k_2}$ and $\varphi = \tan^{-1} \left(\frac{K_x}{K_z} \right)$ [12-14].

3.1 Relationship between angular and spectral diffraction efficiency: modeling and characterization

A 2D representation of the diffraction efficiency (DE) as a function of angles and wavelengths is shown in Fig 2. In this figure darker shading represents higher DE, and the center of the line represents the angular-spectral Bragg condition that is obtained when equation (6) is equal to zero. In practice the DE is measured either as a function of angle (scanning angle at a fixed wavelength), and/or as a function of reconstruction wavelength (scanning wavelengths at a fixed angle) as shown in Fig 2. Therefore, the angular DE and spectral bandwidth of the hologram can be obtained from equation (4) as,

$$DE_a(\theta) = DE(\theta, \lambda = \lambda_r) \quad (8)$$

$$DE_s(\lambda) = DE(\theta = \theta_r, \lambda) \quad (9)$$

where θ_r, λ_r are the readout angle and wavelength respectively.

Characterization of the angular DE requires a set of monochromatic lasers, a rotation stage and a detector. This measurement is less demanding than a spectral DE characterization that would require the use of several tunable lasers of very small spectral width to cover the potentially large range of operation of S²-VHIS (450nm – 900 nm).

For the highly selective holograms used in the S²-VHIS ($\Delta\theta < 0.04^\circ$ and $\Delta\lambda < 0.4 \text{ nm}$) it is possible to estimate the spectral DE bandwidth from an angular DE measurement . Using $\theta = \theta_b + \Delta\theta$ and $\lambda = \lambda_b + \Delta\lambda$ in equation (6), where θ_b and λ_b are the angle and wavelength

satisfying the Bragg condition, and $\frac{\Delta\theta}{\theta_b} \ll 1$ $\frac{\Delta\lambda}{\lambda_b} \ll 1$, the following equation is obtained [10-12].

$$\vartheta(\Delta\theta, \Delta\lambda) = -K \sin(\varphi - \theta_b) \Delta\theta + \frac{K^2}{4\pi n_2} \Delta\lambda \quad (10)$$

The other parameters of the DE can be approximated as

$$\nu(\theta, \lambda) = \nu(\theta_b, \lambda_b) = cte \quad ; c_s(\theta) = c_s(\theta_b) = cte \quad ; c_r(\theta) = c_r(\theta_b) = cte \quad (11)$$

Replacing (10-11) in (4) the diffraction efficiency for a small deviation from the Bragg condition can be obtained,

$$DE(\theta, \lambda) = DE(\theta_b + \Delta\theta, \lambda_b + \Delta\lambda) = DE^\circ(\Delta\theta, \Delta\lambda) \quad (12)$$

Therefore, for small angular and spectral deviation from the Bragg condition it is possible to find equivalence between angular and spectral DE as follows,

$$DE_s(\Delta\lambda) = DE_a\left(\Delta\theta = \left(\frac{K}{4\pi n_2 \sin(\varphi - \theta_b)}\right) \Delta\lambda\right) \quad (13)$$

Although the arguments of these DE function are different, they have similar profiles as illustrated in Fig. 2.

3.2 Non uniform index modulation along the grating depth

Photopolymers such as PMMA mixed with PQ dyes are useful materials for obtaining inexpensive thick volume holograms. However, the high attenuation of the constructing beams [14] during recording produces a non-uniform index modulation along the grating depth. That ultimately limits the effective thickness of the hologram [18-20]. The attenuation of non-exposed PQ-PMMA medium at recording wavelengths is particularly high as seen in Fig.3 [9].

There are several methods to study the effect of this attenuation during recording on the properties of the resultant hologram [15-19]. Here ACWA[12-14] and the transfer matrix method [15] are employed.

The index modulation of a sinusoidal grating can be expressed by,

$$dn(z) = \Delta n f(z) \quad (14)$$

where $f(z)$ is a slowly-varying modulation function in the direction of the hologram thickness caused by the effect of absorption during the recording process. The range of values for $f(z)$ is 0 to 1, therefore Δn is the peak index modulation. A non-uniformly modulated grating of thickness t_H is divided into a set of N uniform gratings of thickness t_H / N . Each grating has a index modulation given by,

$$dn_i(z) = \Delta n f\left(i \frac{t_H}{N}\right) \quad (15)$$

where i is the grating element number.

For each grating, the amplitude transfer function of the zero-order propagating beam $T^0(\theta, \lambda)$ and the first-order diffracted beam $T^1(\theta, \lambda)$ is calculated as described in [15,17],

$$T^1(\theta, \lambda) = j \sqrt{DE(\theta, \lambda)} \quad (16)$$

$$T^0(\theta, \lambda) = \cos\left(\sqrt{\nu(\theta, \lambda)^2 + \xi(\theta, \lambda)^2}\right) + \frac{\xi(\theta, \lambda)}{\nu(\theta, \lambda)} T^1(\theta, \lambda). \quad (17)$$

The transfer matrix for each grating element is then given by

$$M_i(\theta, \lambda) = \begin{vmatrix} T^0(\theta, \lambda) & T^1(\theta, \lambda) \\ T^1(\theta, \lambda) & (T^0(\theta, \lambda))^* \end{vmatrix} \quad (18)$$

where $*$ indicates the conjugate operation. The coherent interaction of all N grating elements is therefore given by the multiplication of the transfer matrices as follows,

$$M(\theta, \lambda) = \prod_{i=1}^N M_i(\theta, \lambda) \quad (19)$$

From (19) the resultant DE can be computed as indicated in [15].

3.3 Definitions of effective thickness

The methodology described above is also used to solve numerically for $f(z)$ by curve matching different index profiles with experimental diffraction efficiency data. A customized gradient algorithm implemented in Matlab™ is utilized to find the index profile $f(z)$ that produces the best match between modeled and measured diffraction efficiency.

The effective thickness is then obtained from $f(z)$ using two methods. The first method is a generalization of the method described in [18-20]. In the original method [18-20] an exponential decay for the index modulation was assumed. In the generalized method used here, $f(z)$ can account for a large set of profiles. One of them is the exponential decay used in [18-20]. This additional degree of freedom produces better matching between the measured and modeled DE.

Using this method, the effective thickness is given by [18-20].

$$t_{eff} = \int_0^{t_H} f(z) dz \quad (20)$$

For the particular case of exponential decay ($f(z) = e^{-\alpha z}$), where α is the index profile attenuation coefficient [18], the effective thickness is obtained as

$$t_{eff} = \frac{1 - e^{-\alpha t_H}}{\alpha} \quad (21)$$

Using equation (20) and the model described above it was found that t_{eff1} serves well to predict the diffractive efficiency of the grating. Larger t_{eff1} produces higher DE as validated in modeling and experiments. However, our modeling and experiments (shown in Section 5) also demonstrate that the angular bandwidth of the grating does not accurately correlate with this effective thickness definition. This is illustrated in the example described below.

Two gratings: A and B, with $f(z) = e^{-z}$ and the same effective thickness ($t_{eff1} = 500 \mu\text{m}$) were modeled. The index modulation peak of both gratings was 3×10^{-4} and the values of α , for gratings A and B, were 1.3 mm^{-1} and 1.95 mm^{-1} respectively. In order to have both gratings with the same t_{eff1} , the total thickness computed by inverting equation (21) as,

$$t_H = \frac{-\ln(1 - \alpha t_{eff1})}{\alpha} \quad (22)$$

resulting in a total thickness of $800 \mu\text{m}$ and $1891 \mu\text{m}$ for A and B respectively.

In Fig. 4 it can be observed that although both gratings have a similar DE peak, their angular bandwidths are significantly different. Additional simulations performed using different index profiles indicate that t_{eff1} is not a good estimator of the angular bandwidth of the gratings. Therefore, another definition of effective thickness, t_{eff2} , is utilized. This parameter is defined as the distance from the front surface of the sample during recording to the depth in which the index modulation reaches a certain percentage of the peak modulation value. This threshold percentage is set to 5%. Experimental results indicate that for the range of thickness used in this investigation (1 mm - 3 mm), an index modulation below 5% of the peak value, does not affect significantly the DE.

4. Resolution dependence on the hologram properties

The imaging capabilities of S^2 -VHIS using holograms recorded in PQ-PMMA have been demonstrated in [3-9]. A lateral resolution capable of resolving spatial frequencies up to $\sim 200 \text{ lppm}$ has been achieved [6-9]. However, this performance is not equal along the vertical and horizontal axes as the mechanism of image formation differs in each direction.

As described in Section 2, the hologram does not affect the image resolution along the y-axis. Along this axis, the resolution is mainly limited by the NA of the objective lens.

The FOV along the x-axis depends on the bandwidth of the broadband source B_λ . Using an LED with 30 nm FWHM bandwidth results in a FOV of $100 \mu\text{m}$. The resolution in the dispersive axis depends on the spectral bandwidth of the hologram, where the maximum number of resolvable points on that FOV is given by

$$N_x = \frac{B_\lambda}{\Delta\lambda} \quad (23)$$

A diagram illustrating this resolution degradation along the x-axis due to the angular dispersion of the hologram is shown in Fig 5. Broadband light from a point source

positioned at the focal length of the objective reaches and is dispersed by the hologram, propagating to the camera where it produces a blurred image of the point source.

The degree of blurring in the dispersive axis can be calculated from the angular DE using the ACWA described previously and shown in Fig 6. In general, the light diffracted by the hologram at a given wavelength λ and a given angle θ reaches the image plane at a position given by

$$x = f_c \tan(\theta) = f_c \tan(\theta_b + \Delta\theta) \approx x_o + f_c \Delta\theta \quad (24)$$

where f_c is the focal length of the collector, $\Delta\theta = m\Delta\lambda$ is the small dispersive angle near the Bragg condition and m is the dispersion slope away from the Bragg condition computed using equations (1,2).

Assuming a spatial invariant system, the point spread function in the dispersive axis $PSF(x)$ can be estimated from the spectral dependence of the DE as,

$$PSF_x(x) \propto DE_s\left(\frac{\Delta\theta}{m}\right) = DE_s(x/mf) \otimes h(x) \quad (25)$$

where $h(x)$ is the intensity PSF component due to the objective lens and other optical elements in the system. Since this investigation is focused on the effects of the hologram on the image resolution, it is assumed that the remaining elements produce diffraction limited PSF. Here it was used $h(x) \approx \delta(x)$ where $\delta(x)$ is the Dirac delta function, to estimate the best-case performance of the S2-VHIS along the x-axis. The modulation transfer function using the can be computed as,

$$MTF_x(f_x) \propto \Im\{DE_s(x/mf)\}, \quad (26)$$

where $\Im\{\}$ represents the Fourier transform operation and $\delta(x)$ is the Dirac delta function.

Equations (25) and (26) indicate that in order to improve the x-axis resolution, the spectral bandwidth of the hologram should be reduced. Approaches to reduce this bandwidth are implemented in the next section.

5. Modeling and Experimental validation

For a hologram with a non-uniform index modulation versus depth profile as occurs with PQ-PMMA, the angular and spectral bandwidth cannot be reduced by simply increasing the physical thickness of the recording medium. Other parameters, such as the shape and effective thickness over which the index modulation function play a more important role.

The effective thickness depends on the material absorption during the recording process as well as the physical thickness of the medium. Absorption of unexposed PQ-PMMA is lower at longer wavelengths as indicated in Fig. 2 [9]. However, the photosensitivity of the recording material also decreases using longer wavelengths [9,20].

The effective thickness for the PQ-PMMA construction geometry used in the S²-VHIS [6-8] was estimated at three wavelengths: 457 nm (HOE 1), 488 nm (HOE 2) and 514 nm (HOE 3). The construction geometry was varied so to keep a constant grating pitch with each recording wavelength. The physical thickness for the three gratings was ~2 mm. Results of

measurements and simulations are shown in Figures 7,8 and 9. The top regions of these figures show the measured DE (marks) and modeled DE (solid line). The bottom regions of the figures show the index modulation profile and effective thickness (5% of peak index modulation definition) obtained using methods described in Section 3.

The measured FWHM angular bandwidth of the three gratings are 0.033° , 0.03° , and 0.025° respectively. The grating exposed with 514 nm has the largest effective thickness ($t_{\text{eff}2}=1.8$ mm) since recording light at this wavelength propagates with less attenuation through the recording media. In general, experimental results were consistent with our expected (from Section 3) monotonically decreasing dependence between the angular bandwidth and $t_{\text{eff}2}$. Experimental results also confirm the inaccuracies of using $t_{\text{eff}1}$ as an estimator of angular bandwidth. The higher $t_{\text{eff}1}$ corresponds to the grating fabricated with 457 nm laser, which has the largest bandwidth.

Using equation (26) the x-axis MTF for the three gratings is estimated from the measured angular bandwidth as shown in Figure 10. This estimation predicts that the grating fabricated at 514 nm should have better performance at higher spatial frequencies (<200 lppm) and a slight degradation at lower spatial frequencies. The improvement at higher spatial frequencies is caused by the reduced FWHM bandwidth of the PSF, whereas the degradation at lower frequencies is caused by small increase of the PSF tails.

The contrast for the x-axis (tangential) and y-axis (sagittal) were measured using an LED at 505 nm. The contrast for the x-axis, shown in Fig 11 shows good agreement with the estimated MTF. Using a grating that has narrow angular bandwidth and larger effective thickness improves the contrast at higher frequencies along the dispersive x-axis.

Fig. 12 shows images of the USAF 1951 Resolution Test Chart group 7 using the three gratings. The last 3 elements of that group, which correspond to spatial frequencies ~ 178 -228 lppm, are better resolved using the grating fabricated with 514 nm.

The contrast along the y-axis for the three holograms was also measured. At spatial frequencies below 128 lppm all gratings have contrast $> 48\%$. At spatial frequencies of 228 lppm all the gratings has a contrast value in the range of $28\% \pm 1\%$. Since performance along the y-axis is dominated by the performance of the objective rather than the hologram, the contrast for each HOE along the y-axis were higher than along the x-axis.

6. Summary and Discussion

The spectral dispersion of the holographic element was analyzed and determined to be one of the main causes of MTF degradation in the S^2 -VHIS. The HOE's spectral dispersion broadens the x-axis PSF resulting in reduced image contrast in the x-axis. Since the y-axis resolution is not affected by the hologram dispersion, an asymmetric MTF is produced in the system.

The MTF dependence of the S^2 -VHIS has been modeled using approximated coupled wave analysis combined with transfer matrix methods. Models predict that MTF improvements require the use of larger effective thickness. The effective thickness is not necessarily related to the physical thickness of the hologram but with the profile of index modulation strength owing to the recording material's absorptive characteristics. The traditional definition of effective thickness, which works well to estimate the diffraction efficiency peak values, does not correlate well with the angular bandwidth of the hologram. A practical definition has been used instead providing good correlation with experiments. The dependence of this effective thickness on recording wavelength for PQ-PMMA S^2 -VHIS has been studied.

The derived modeling techniques have been applied to improve the resolution of current S²-VHIS prototypes. Results indicate the potential of achieving similar resolution in both axes and to extend the resolution over 228 lppm. The modeling techniques described in this paper are being used to further enhance the resolution of new S²-VHIS prototypes.

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Fig. 1.
Layout and basic description of the S²-VHIS operation

Fig. 2. Relationship between the angular and spectral DE for angles and wavelengths close to the Bragg condition.

Fig. 3.
PQ-PMMA absorption for exposed and unexposed material.

Fig. 4.
Index modulation profile (LEFT) and DE (RIGHT) of two gratings with identical t_{eff1} .

Fig. 5. HOE chromatic dispersive properties produce degradation in the x-axis image resolution. A point source in object space forms a blurred spot along the dispersive axis of the S^2 VHIS

Fig. 6.
Relationship between spectral DE and angular dispersion

Fig.7. (Top) Measured DE (square marks) and modeled DE (solid gray line) for the HOE constructed at 457 nm (HOE 1) (Bottom) Index modulation profile. Effective thickness =1.32 mm using the 5% peak criteria.

Fig.8. (Top) Measured DE (square marks) and modeled DE (solid gray line) for the HOE constructed at 488 nm (HOE 2). (Bottom) Index modulation profile. Effective thickness =1.55 mm using the 5% peak criteria.

Fig.9. (Top) Measured DE (squares) and modeled (DE) (solid gray line) for the HOE constructed at 514nm (HOE 3) (Bottom) Index modulation profile. Effective thickness =1.8 mm using the 5% peak criteria.

Fig. 10.

X-axis MTF for the three holograms: (Triangular marks) HOE 1 (457 nm). (Square marks) HOE 2 (488 nm) . (Gray line) HOE 3 (514.5 nm)

Fig. 11.
X-axis contrast measurements for the three holograms: (Triangular marks) HOE 1 (457 nm) . (Square marks) HOE 2 (488 nm) . (Gray line) HOE 3 (514.5 nm)

Fig. 12. Image of the Air Force Bar Chart 1951, Group 7 reconstructed at 505nm. Image produced using a) HOE1 (457 nm) . b) HOE 2 (488 nm) . c) HOE 3 (514.5 nm).