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Confocal-Rainbow Volume Holographic Imaging System

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The performance of broadband volume holographic imaging system in terms of depth selectivity is investigated. The mechanism for depth resolution degradation is explained. In order to overcome this resolution degradation a novel imaging device, the Confocal-Rainbow Volume Holographic Imaging System, is proposed. Modeling and experimental validation of the performance of this novel imaging system indicates that depth resolution $< 16 \mu\text{m}$ is achievable. The lateral resolution of this device is $< 2.5 \mu\text{m}$ along a field of view of $300 \mu\text{m} \times 100 \mu\text{m}$.

1. Introduction

High resolution three-dimensional (3D) optical imaging instruments, such as confocal microscopes and optical coherence tomography systems are important tools in biological and medical research [1].

During the last decade, volume holographic imaging system (VHIS), which uses the hologram's wavefront selection properties to simultaneously select images from multiple object depths, has been developed [2-9]. They achieved lateral and depth resolution of $\sim 3 \mu\text{m}$ and $\sim 12 \mu\text{m}$ respectively when using mono-chromatic illumination and standard lens components [2-8].

The disadvantage of using a monochromatic source is that lateral scanning is required in order to capture the complete image field. Using a broadband source has been proposed and implemented in [5-9] with the goal of avoiding mechanical scanning while maintaining the resolution achieved using monochromatic sources. However, in practice, the utilization of a broadband illuminator reduces dramatically the depth sectioning capabilities of VHIS. This has been previously observed in reference [5-9], although a clear description of the physical causes of this degradation in the axial resolution has not yet been explained.

An approach to improve depth resolution which utilizes a rainbow illumination pattern produced by the diffraction of a broadband source on an external grating was proposed [9]. This type of VHIS configuration has been shown capable of improving the depth resolution to values over $200 \mu\text{m}$. There are limitations for improving depth resolution beyond that value using this configuration since it requires accurate matching the wavefront of the external gratings (illuminator hologram) and internal grating (imaging hologram).

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In this paper comprehensive models described in [10-11,13-15] are utilized to explain the causes for the lost of depth selectivity when broadband illuminators and a novel approach to solve this problem is proposed. A key aspect of the proposed approach is to use the same path for dispersing the light, illuminating the object and obtaining an image from it. Our modeling shows that using this configuration, not only is there a perfect match between the spectral-spatial properties of the illumination and the reflected light that produced the image, but also a confocal effect –comparable to slit confocal microscopes– is incorporated in the imaging system. This results in a significant enhancement of the depth resolution ($\sim 10X$) and some improvements to the lateral resolution ($< 2X$). An advantage of our approach compared with slit confocal microscope is that the slit images of several sample depths can be obtained simultaneously without any need for scanning.

The remainder of this paper is divided in five sections. In section 2 the basic operation VHIS is described. In section 3 the effects of the broadband illumination on the depth resolution of the system is described. In section 4 we describe a model for our proposed approach: the confocal-Rainbow VHIS (CR-VHIS). Section 5 shows experimental results of our first prototype. A summary of our work is presented in Section 6.

2. VHIS: basic layout and operation

The basic configuration of a VHIS consists of a 4F system with a holographic element placed in the Fourier plane [5-8]. The holographic element is composed of thick angle-multiplexed planar and spherical wave gratings with high angular and spectral selectivity. The construction parameters for this type of hologram has been explained in [5-8,12].

Due to the high grating selectivity, each grating when illuminated with a monochromatic point source, selects a specific wavefront that originates at a particular depth from within the scattering object. Multiplexing several gratings into the same volume allows mapping points from multiple depths in object space to the image plane.

The layout depicted in Fig 1. serves as an example of the VHIS operation. In this figure a broadband source is used as the illuminator. For each plane in the object space, mapping is produced by two properties of volume holograms [5-8,10,13-15] : (1) the spatial degeneracy and (2) the angular dispersion. Due to the first property, the wavefront of a point source at any position along the y-axis satisfies the Bragg phase matching condition of the holographic optical element (HOE) and therefore is diffracted to the collector lens. This diffraction is responsible of the y-axis field of view. Current prototypes using a set of relay lenses (not shown in Fig. 1) have achieved a y-field of view of ~ 1 mm [6]. The FOV along the spatial degeneracy axis does not follow a straight line along the y-axis as indicated by the cylinder axis shown in Fig 1, but hyperbolic curves as described in [10].

The lateral resolution in the y-axis depends mainly on the numerical aperture (NA) of the objective lens. The angular dispersion of the hologram and the spectral bandwidth of the readout source determine the FOV in the x-axis. The lateral resolution along the dispersive axis (x-axis) depends on the spectral selectivity of the hologram which can be improved by optimizing its fabrication parameters [6-8,11].

For a VHIS operating with monochromatic illumination the depth selectivity depends on the NA of the objective lens (Lo) and the angular bandwidth of the hologram. In this configuration scanning is required to capture the x-axis FOV. Recently, VHIS prototypes using monochromatic sources have achieved lateral resolution of $2.5 \mu m$ [2] and depth resolution of $\sim 12 \mu m$.

However, when a broadband light source is utilized as an illuminator in the VHIS the depth selectivity is essentially lost. Figure 2 shows images obtained using a VHIS of an Air Force Bar Chart 1951 scanned at three different depths. The images were obtained using a 505 nm LED with bandwidth of ~ 30 nm. The VHIS used a bright field broadband illumination configuration. That figure shows that the image sharpness in the high resolution patterns is degraded as the object goes out of focus. However, the total energy in the image remains almost constant. A similar experiment using a confocal microscope would have shown significant reduction in the image energy as it goes out of focus.

3. Broadband Effects on VHIS Depth Resolution

A combined imaging and diffraction efficiency model for focusing holographic elements discussed in references [10-11] were used to study the causes of depth resolution degradation in VHIS. This model include Approximated Couple Wave Analysis (ACWA) [13-15], transfer matrix [18-20] combined with a non-sequential ray tracing algorithm software [10].

Figure 3, 4, and 5 show simulated layouts used to describe the depth resolution degradation. The hologram shown in these figures was recorded using two planar beams at wavelength λ_0 . For simplicity our analysis begins assuming an ideal hologram (100% diffraction efficiency and negligible angular bandwidth) and ideal lenses operation (no aberrations).

Figure 3 shows the operation when a monochromatic point-source (PS) at wavelength λ_0 is utilized. Initially, the point source is located at the focal length of the objective lens. Light emitted by this point source is collimated by the objective lens (dashed line) and propagates to the hologram. The hologram diffracts this beam to a collector lens that focuses the light on the camera aperture. By moving the point source to an out-of-focus position, $\Delta z > 0$, (solid line), a spherical wavefront is produced by the objective lens. This spherical wavefront beam does not match the Bragg condition along the hologram aperture. The amount of light diffracted depends on the amount of defocus, the numerical aperture of the objective lens, and the hologram angular bandwidth. Analytical expression for VHIS depth selectivity prototypes using monochromatic sources has been derived in [3]. A path to improve the depth selectivity is to reduce the angular bandwidth of the hologram as experimentally demonstrated in [11]. Currently, VHIS prototypes using monochromatic sources achieve depth resolutions of $12 \mu\text{m}$ [7-8].

The operation of a volume holographic imaging system using a broadband illumination varies significantly. Figure 4 shows a broadband point source with center wavelength λ_0 located at the focal point of the objective lens. It is shown in this figure that the grating diffracts the light at one wavelength (λ_0) as in the monochromatic case (Fig. 3). However, for out-of-focus points, $\Delta z \neq 0$, most of the energy from the point source is not rejected. The hologram still diffracts light to the camera as shown in Figure 5. There is always one wavelength inside the bandwidth of the source capable of matching the Bragg condition inside the hologram aperture. Since more than one wavelength is used to image the point source from the object space to the image plane, the volume hologram does not participate in the depth selectivity as it does in the VHIS with monochromatic point source. In this broadband operation condition, the objective lens produces blurred images of out-of-focus points, but it does not reject the energy of out-of-focus points. Therefore the contrast is poor and depth resolution is highly degraded.

For completeness in the description of depth resolution degradation, our analysis, include the case of non-ideal HOE. Simulations shown below utilize a hologram with peak diffraction wavelength at 505 nm, a full width half maximum (FWHM) angular bandwidth $\Delta\theta = 0.02^\circ$ and a FWHM spectral bandwidth $\Delta\lambda \sim 0.4$ nm. For both cases, an objective lens

with numerical aperture (NA) of 0.5 was used and the center wavelength of the source was $\lambda_0=505$ nm. The spectral FWHM bandwidth of the broadband source was 20 nm.

Figure 6 shows the axial point spread function (z-PSF) of the VHIS for several wavelengths as a function of defocus. The z-PSF was computed by moving the point source along the z axis and integrating the energy capture by the camera. The FWHM bandwidth for the z-PSF at λ_0 (solid black line in Figure 6) represents the depth selectivity of a VHIS using monochromatic source.

When this VHIS is used with a broadband illuminating source, the broadband z-PSF shape is the weighted average of the z-PSFs for each wavelength inside the source spectrum. The weighted factors depend on the spectrum profile of the source. The broadband z-PSF shown in Figure 6 (dotted lines) indicates that the depth selectivity is significantly degraded. The degree of this degradation depends on the bandwidth of the illuminating source. For the parameters used for this simulation, the depth selectivity was >15 times worse than the resolution of the VHIS with monochromatic source.

The mechanism for the depth selectivity degradation has been described qualitatively using ideal HOE (Figures 4-5) and quantitatively for typical HOE used in VHIS (Figure 6). Both descriptions show a significantly reduction in depth resolution when broadband sources are used.

The reason is that at defocus ($\Delta z \neq 0$) most of the wavelengths of the source spectrum satisfy the Bragg condition at some specific region of the HOE aperture (Figure 5). Since this Bragg matching condition is satisfied at a specific position in the HOE aperture, only a fraction of the light energy for each wavelength is diffracted by the HOE toward the camera. For example, in Figure 6 it is shown that at $\Delta z = -15$ μm , the energy reaching the camera for each wavelength is small (< 13% of the peak energy at $\Delta z = 0$). However, there are more wavelengths with non-zero energy values at that defocus position. Therefore, the total energy resultant of the contribution of all these wavelengths is comparable to the energy collected at $\Delta z = 0$.

From the analysis presented above, it seems possible to improve the axial resolution by reducing the bandwidth of the source. However, this approach at the same time reduces the FOV in the dispersive axis and therefore one-axis lateral scanning is required to capture the complete x-axis FOV.

An approach proposed to improve the selectivity without requiring lateral scanning utilizes a rainbow illumination described in [9]. A simplified layout of this approach using transmission HOE is shown in Fig. 7. This approach requires two sets of gratings and lenses: one to provide the illumination and the other for imaging. The rainbow illumination is produced by the dispersive properties of the illuminating HOE. Ideally the illumination plane should overlap the object plane along the complete FOV. Also the spectral dispersion produced by each set of optical elements should match. Although this ideal condition cannot be fully attained with the layout shown in Fig. 7, the application of this method improved the depth resolution to values ~ 200 μm as shown in [9]. Better depth resolution than this requires better dispersion matching between the external grating (illuminator) and the internal grating (imaging) not only in the optical axis but over the complete FOV in the object plane. Also, even if that challenging condition is satisfied, an overlap between the illumination and object plane is required. For imaging systems with using objective lens with $\text{NA} > 0.5$ the latest condition is not attainable with external illumination. For example Fig. 7 shows that there is a tilt angle, ϵ , between the object plane and illuminating plane. This angle, which takes values of ~ 60 deg. for lenses with $\text{NA}=0.5$, reduces significantly the region in which the object and illuminating plane overlaps.

4. Design and Simulation of the Proposed Confocal- Rainbow VHIS concept

It is proposed here to use the same light path for illuminating and imaging the object in order to overcome the mismatch problem of the dispersive characteristics of the illuminator and imaging components of the rainbow VHIS shown in Figure 7. Figure 8 illustrates this configuration. In this schematic a beam splitter (BS) is used to reflect an illuminating beam to the hologram (HOE) which is tilted at specific angles $\{\theta, \beta\}$ to maximize the FOV and minimize stray light reflections. The illuminator emitting area (A) and angle (α) are designed to fill both the aperture of the HOE and its acceptance angle after being reflected by the beam splitter.

In this imaging device, light passes through the hologram and objective lens twice: once to produce the illumination, and again to produce the image. The double light pass through the objective lens results in a spatial filtering effect comparable to that found in a slit confocal microscope. The double pass through the hologram improve the filtering of the light and produce a rainbow pattern in the object plane as shown in Fig. 9.

In this Figure, the spread of each color (wavelength) of the source spectrum is represented as a slit. The width of each slit (color), which is exaggerated in the figure, depends on the angular bandwidth of the hologram and therefore on the effective thickness and index modulation profile of the hologram [11].

The diffractive pattern shape follows the function, $F(x,y,\lambda,K)$ as shown Fig. 9. This function represents a set of conic curves where x and y is the position in the object plane, λ , the wavelength illuminating this position and K the grating vector. The function, $F(x,y,\lambda,K)$ can be derived from the Bragg condition [11] and also from the Born approximation [21]. In [11] it was demonstrated that in most cases the diffractive field forms hyperbolic patterns. For HOE with negligible angular bandwidth, there is only one curve for each λ . However, in practice, there is a finite width for each color which is in general one of the main limiting factors in all VHIS configurations [2-9].

Simulations of the depth selectivity of the configuration shown in Fig 8 were performed using ACWA and ray tracing model. For this simulation a source with spectral bandwidth of ~30 nm was utilized. A hologram with one grating was used to test the conceptual design. The hologram was constructed with two planar waves at angles ± 34 deg. Construction details of the hologram can be found in [5-8]. Ideal lenses were assumed. The focal length and NA of the objective lens were 3.5 mm and 0.55 respectively. The focal length of the collector lens was 20mm.

Initially, a standard VHIS [2-5] with similar HOE and lenses to the one described above were simulated using monochromatic and broadband point source as shown in Section 3. For the case of mono-chromatic source it was obtained a z-PSF with FWHM resolution ~ 12 μm . For the broadband source however, the z-PSF has almost a constant energy value for depths in the range of $\pm 120 \mu\text{m}$ from focus.

In case of the Confocal - Rainbow VHIS, the simulated object consisted of a mirror covered with an amplitude mask with parallel lines at spatial frequencies in the range from 20 to 220 lppm. This object allows more realistic comparison with experimental measurements where a reflective Air Force Bar Chart Pattern was used. To test the performance of the system this object was moved from focus to defocus positions ($-50\mu\text{m} < \Delta z < 50 \mu\text{m}$). The image and its energy were obtained for different depths. The energy was estimated by integrating the intensity in the complete FOV.

The resulting z-PSF and images shown in Fig. 10 indicate that depth resolution is comparable to the VHIS operating with monochromatic source. The energy of the object image decreases as it goes out of focus as shown in the insets of figure 10. A FWHM depth resolution of $\sim 13 \mu\text{m}$ was obtained. For defocus $> 20 \mu\text{m}$ microns the energy reduces to 0.15 of the peak value and the image almost disappears in the simulated linear-scaled detector.

Therefore, numerical modeling indicates that axial resolution which is significantly degraded when using a broadband source can be almost recovered using the confocal – rainbow approach proposed here. This is a depth resolution improvement of $\sim 10\times$ compared with original rainbow VHIS concept.

However Confocal-Rainbow VHIS require careful design to minimize undesired reflection noise from the beam splitter and the hologram surface. In order minimize the specular reflection of the source to the detector the hologram must be tilted around the x-axis, ($\beta > 0$) to redirect reflected light out of the imaging path. Although, the precise value of this rotation depends on the layout of the system, simulation and experimental suggest $\beta \sim 10$ degrees to reduce this reflection. In addition the illumination aperture size, A_i and emitting angles, α_i , must be designed to fill the aperture of the hologram, as well as the hologram angular acceptance range. in order to illuminate the entire field of view efficiently. These design consideration were utilized in the Confocal-Rainbow implementation shown in next section.

5. Experimental Validation

The setup indicated in Fig. 8 was implemented using a broadband illuminator, a pellicle beam splitter and a hologram with a single grating with parameters indicated in Section 3. An objective lens with NA of 0.55 was utilized. The objective and collector lenses (see figure 8) were similar to the ones used in Section 4.

A reflective Air Force Bar Chart 1951 was utilized as an object for the conceptual design demonstration. Motorized stages were used to control the axial position of the object. A six-megapixel camera with pixel size of $3.5 \mu\text{m}$ was utilized to capture the images. A program written in Matlab™ was used to control the axial position object, capture the images and to compute the energy of the entire FoV of the images.

Experimental result for the z-PSF and images at different depths are shown in Fig 11. The field of view of the images was $300 \mu\text{m} \times 100 \mu\text{m}$. The z-PSF FWHM bandwidth obtained was around 15 microns. The images indicate that at focus it is possible to resolve feature of around 2.5 microns that correspond to the Group 7 element 6 of the Air Force Bar Chart 1951.

The images show clearly that not only the sharpness but the energy of the out of focus images is reduced. This is different to images obtained with the standard VHIS (Fig. 2) in which only the sharpness but not the energy decreases as the object goes out of focus.

6. Conclusions

Broadband illumination is desired in volume holographic imaging systems since they reduce or eliminate the need for mechanical scanning. However, they produce significant depth resolution degradation in the imaging system.

A comprehensive numerical model was used in this paper to simulate the operation of the VHIS for both the monochromatic and broadband illumination cases and to describe the causes of depth selectivity degradation using broadband illuminators.

A novel VHIS design, the Confocal Rainbow Volume Holographic Imaging System, was proposed to solve the problem of depth degradation. A prototype was implemented and tested. Simulation and experimental validation confirms that a depth resolution of 15 μm using a broadband source can be achieved. This is comparable to the resolution of VHIS using monochromatic source (12 μm).

The Confocal-Rainbow VHIS prototype obtained ten times better depth resolution than other broadband VHIS prototypes previously proposed. This new imaging device can be potentially used in a broad range of applications, particularly in the fields of 3D biomedical imaging and profilometry. Depth resolution of Confocal Rainbow VHIS is dependent on the hologram selectivity as in the case of VHIS using monochromatic illumination. Therefore, the selectivity of the Confocal Rainbow Illumination VHIS prototype can be further improved by increasing the holograms selectivity using techniques discussed in [11,13-15].

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References

1. Fujimoto, J.; Farkas, D. Biomedical optical imaging. Oxford: 2009.
2. Liu W, Psaltis D, Barbastathis G. Real-time spectral imaging in three spatial dimensions. *Opt. Lett.* 2002; 27:854–856. [PubMed: 18007950]
3. Arnab, Sinha; Sun, Wenyang; Shih, Tina; Barbastathis, George. Volume holographic Imaging in the Transmission Geometry. *Applied Optics.* 2004; 43(7):1533–1551. [PubMed: 15015536]
4. Li Z, PSaltis D, Liu W, Johnson WR, Bearman G. Volumen Holographic Spectral Imaging. *Proc. SPIE* 5694. 2005; 33
5. Arnab Sinha and George Barbastathis. Broadband volume holographic imaging. *Applied Optics.* 2004; 43(27):5214–5221. [PubMed: 15473242]
6. Luo Y, Gelsinger PJ, Barbastathis G, Barton JK, Kostuk RK. Optimization of multiplexed holographic gratings in PQ-PMMA for spectral-spatial filters. *Opt. Lett.* 2008; 33:566–568. [PubMed: 18347711]
7. Gelsinger-Austin PJ, Luo Y, Watson JM, Kostuk RK, Barbastathis G, Barton JK, Castro JM. Optical design for a spatial-spectral volume holographic imaging system. *Opt. Eng.* 2010; 49
8. Luo Y, Castro JM, Barton Jennifer K, Kostuk Raymond K, Barbastathis George. Simulation and experiments of aperiodic and multiplexed gratings in volume holographic imaging systems. *Optics Express.* Aug.; 2010 18(18):19273–19285. [PubMed: 20940823]
9. Sun, Wenyang; Barbastathis, George. Rainbow volume holographic imaging. *Optics Letters.* May. 2005 30(9):976. [PubMed: 15906975]
10. Castro JM, de Leon E, Barton Jennifer, Kostuk Raymond. Analysis of diffracted image patterns from volume holographic imaging systems and applications to image processing. *Applied Optics.* 2010 Accepted for publication on November.
11. Castro JM, Brownlee J, de Leon E, Barton J, Kostuk RK. Resolution Dependence on index modulation profile and effective thickness in volume holographic imaging systems. Submitted to *Applied Optics.* Sept.2010
12. Sato A, Kostuk RK. Holographic grating for dense wavelength division optical filters at 1550 nm using phenanthrenequinone doped poly(methylmethacrylate). *Proceedings of SPIE Vol 5216 Organica Holographic Materials and Applications.*
13. Kogelnik H. Coupled wave theory for thick hologram gratings. *Bell Syst. Tech. J.* 1969; 48:2909–2947.
14. Solymar, L.; Cooke, DJ. Volume Holography and Volume Gratings. Academic Press; 1981.
15. Goodman, JW. Introduction to Fourier Optics. McGraw-Hill; 1996.

16. Moharam MG, Gaylord TK. Three-dimensional vector coupled-wave analysis of planar-grating diffraction. *J. Opt. Soc. Am. OSA*. 1983; 73(9):1105–1112.
17. Moharam MG, Gaylord TK. Rigorous coupled-wave analysis of planar-grating diffraction. *J. Opt. Soc. Am.* 1981; 71:811–818.
18. Kermish D. NonUniform Sinusoidally Modulated Dielectric Gratings. *Journal of Optical Society of America*. 1969; 59(11):1409–1414.
19. Kowarschik R. Diffraction Efficiency of Attenuated Sinusoidally Modulated Gratings in Volume Holograms. *Journal of Modern Optics*. 1976; 23(12):1039–1051.
20. Kubota T. The diffraction efficiency of holograms gratings recorded in an absorptive medium. *Optics Communications*. 15(3):1976.
21. Oh, Se Baek; Watson, Jonathan M.; Barbastathis, George. Theoretical analysis of curved Bragg diffraction images from plane reference volume holograms. *Applied Optics*. 2009; 48(31)

Fig. 1.
Basic layout of VHIS using a broadband source. L_o : objective lens, L_c : collector lens.

Fig 2.
Three images of Air Force Bar Chart at different depths using broadband VHIS show that there is not depth selectivity.

Fig. 3. VHIS using mono-chromatic illumination. Only light on Bragg condition is capable of mapping points in the object space to the image plane. PS= point source.

Fig. 4. VHIS using broadband illumination. At focus case $\Delta z = 0$, shows the mapping from object space to image space uses only a narrow region of the spectrum, centered at λ_0 .

Fig. 5. VHIS using broadband illumination. Out-of-focus case $\Delta z \neq 0$, shows the mapping occurs at any wavelength of the spectrum. Therefore, matching the Bragg condition, required in the monochromatic VHIS is not relevant here. There is essentially no depth selectivity dependence on the hologram.

Fig. 6.

z-PSF for VHIS for different wavelengths. The z-PSF for a VHIS using monochromatic source at $\lambda_0=505$ nm is shown in solid black color. The z- PSF FWHM bandwidth at λ_0 is ~ 9 μm . The z-PSF of a VHIS using a broadband source, which is the average of monochromatic z-PSFs is shown in dotted black color. Vertical axis represents PSF or energy collected at the camera (arbitrary units in this axis).

Fig.7.

Rainbow illumination concept with external illuminator. R and B are to points in the object plane that are imaged using a red and blue wavelength. The ideal illuminator will match the positions and wavelengths of R and B. However, it is shown that the illuminated plane is tilted and the illuminating points with red and blue wavelength are R' and B'.

Fig. 8. Basic schematic of the proposed Confocal-Rainbow Volume Holographic Imaging System. The schematic shows two coordinated systems for the object and HOE plane used in the numerical simulation. The angle θ is the angle subtended between the X and X_h axis. The angle β indicates an additional rotation along the X_h axis to avoid that reflection on the HOE surface reach the camera.

Fig. 9.
Rainbow illumination projected in the object plane.

Fig.10. Modeled z-PSF of the Confocal-Rainbow Volume Holographic Imaging System. The y-axis represent the energy integrate along the complete FoV. Inset show the image observed in the camera.

Fig.11. z-PSF of Confocal-Rainbow Volume Holographic System and images obtained at several depths. E, energy in arbitrary units.