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A novel speckle angular-shift multiplexing for high-density holographic storage

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ABSTRACT

The volume holographic optical data storage has been an important and exciting area of research. Recently the more interested study for a high-density holographic memory is focused on the speckle wave used as the coded reference wave in various multiplexing techniques. In this paper, a novel speckle holographic storage scheme is proposed, which a random phase diffuser is added in the front of storage medium along the reference optical path of the original 90 degree storage geometry. In this scheme the incident angle of the reference beam and the place of the random phase diffuser illuminated by the reference beam can be changed simultaneously. The joint action of these changes generated a dynamic speckle wave for the reference beam in holographic storage. A theoretical model has been derived to describe the storage properties of this scheme based on the cross-correlation of dynamic speckle and the diffractive theory. The storage density influenced by the properties of the speckle patterns has been analyzed and experimentally confirmed. The results indicate that this scheme allows an increase in the data storage density with simple storage-retrieval architecture.

Keywords: Holographic storage, dynamic speckle, high-density, angular-shift multiplexing.

1. INTRODUCTION

Volume holographic data storage and processing offer the potential for high capacity inherent in bulk media, fast access owing to optical addressing, and fast transfer rates owing to their parallel nature[1]. Multiple holograms may be stored in the same volume by use of, i.e., wavelength[2], angular[3], shift[4], and phase encoding[5], typically in a volume Fourier holographic arrangement[6]. These multiplexing methods of volume holograms are based on the selective reconstruction of specific holograms out of an entire ensemble of holograms stored in the medium. Although all these methods permit high-density storage of the holograms, the longitudinal shift component of the volume-recording medium has not been considered for coding the individual pages of information. Recently V.Markov et al.[7,8] used speckle encoded reference beam to demonstrate a single volume, multilayer holographic optical memory based on the features of three-dimensional spatial-shift selectivity in a volume hologram. Their recording method permits more efficient use of the recording medium and yields greater storage density than the spherical or plane-wave reference beams.

According to V.Markov's method, a novel scheme is adopted to realize the same storage performance by using the dynamic speckle rather than the static speckle. It is convenient to use this scheme in the general system of holographic storage by use of angular multiplexing. A random phase diffuser is placed in front of the storage medium and the reference beam transmitted through it with different incident angle into the storage medium. Along with the incident angle change, the illuminated part of diffuser shifted simultaneously. The joint action of these two kinds of variations will transform the original collimated reference beam into a dynamic speckle, as illustrated in Fig.1.

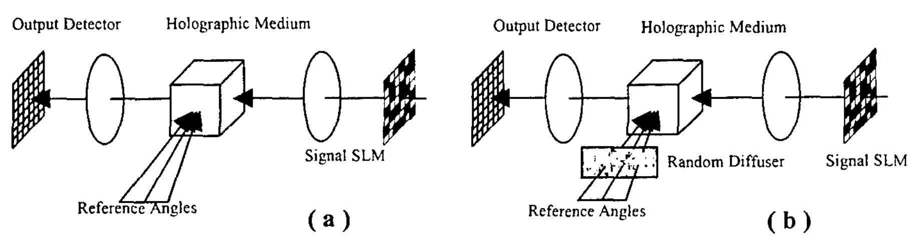

Fig.1. (a) General schematic for holographic storage by angular multiplexing. A signal is generated by an illuminated amplitude spatial light modulator (SLM), and reference beams are incident at different angles. (b) The reference beams are generated by illuminating an random phase diffuser with different incident angles and positions simultaneously.

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In this paper, a theoretical model has been derived to describe the storage properties of this system based on the cross-correlation of dynamic speckle and the diffractive theory. The numerical calculation of the model indicates that the angular selectivity for angular multiplexing has been improved by adjusting the speckle size and so the storage density has been increased. The function of dynamic speckle reference beam is showed to be the same as the static speckle reported by V.Markov. The experiment results farther confirm that the model is competent for describing the holographic storage with dynamic speckle reference beam.

2. THEORY

Let us consider a volume phase hologram recorded with reference speckle wave (writing wave) $R_W(\vec{r})$ and plane wave (signal wave) $S_0(\vec{r}) = A\exp(i\vec{k}_{S_0}\cdot\vec{r})$ of the amplitude A using a 90 degree storage geometry. We assume that after exposure the permittivity $\varepsilon(\vec{r})$ of the recording material will exhibit local changes $\varepsilon(\vec{r}) = \varepsilon_0 + \delta\varepsilon(\vec{r})$ and $\delta\varepsilon(\vec{r})$ is the modulated component of the permittivity. The value of $\delta\varepsilon(\vec{r})$ is supposed to be proportional to the square of the electric field of the interacting waves, i.e.

$$\delta\varepsilon(\vec{r}) \propto |E|^2 = \left|\vec{S}_0(\vec{r}) + \vec{R}_W(\vec{r})\right|^2 \propto S_0(\vec{r})R_W^*(\vec{r}) \tag{1}$$

Now we consider the reconstruction of the hologram influenced by the reading speckle wave $R_R(\vec{r})$. Propagation of transmitted $R_R(\vec{r})$ and diffracted $S(\vec{r})$ waves in the volume of the hologram can be described through the system of Maxwell's equations[9]. For the monochromatic waves of identical polarization in an isotropic media, the system can be reduced to a scalar wave equation

$$\Delta E(\vec{r}) + [\varepsilon_0 + \delta\varepsilon(\vec{r})]k_0^2 E(\vec{r}) = 0 \tag{2}$$

In the first Born approximation, the total field $E(\vec{r})$ in the hologram be presented as an incident reference wave $R_R(\vec{r})$ plus a result of diffracting, $S(\vec{r})$, i.e.

$$E(\vec{r}) = R_R(\vec{r}) + S(\vec{r}) \tag{3}$$

Substituting the total field (3) into the Helmholtz equation (2) and considering that $S(\vec{r})$ is of the first order with respect to the perturbation parameter $\delta\varepsilon(\vec{r})$, then the diffracting field $S(\vec{r})$ satisfies the equation

$$\Delta S(\vec{r}) + k_0^2\varepsilon_0 S(\vec{r}) = -\delta\varepsilon(\vec{r})k_0^2 R_R(\vec{r}) \tag{4}$$

the solution of (4) can be presented as

$$S(\vec{r}) = -k_0^2\int_{-\infty}^{\infty}\delta\varepsilon(\vec{r})R_R(\vec{r})G(\vec{r},\vec{r}\,')dV'$$

$$\cong -Ak_0^2\exp(i\vec{k}_{S_0}\cdot\vec{r})\int_{-\infty}^{\infty}R_W^*(\vec{r})R_R(\vec{r}\,')G(\vec{r},\vec{r}\,')dV' \tag{5}$$

where

$$G(\vec{r},\vec{r}\,') = -\frac{1}{4\pi}\frac{\exp[ik_0|\vec{r}-\vec{r}\,'|]}{|\vec{r}-\vec{r}\,'|}$$

is Green's function.

In the novel scheme for speckle holographic storage, the variation of reference wave includes both changes of incidence angle and shift of illuminating part on the random phase diffuser simultaneously. For the sake of simplification, we assume that the central direction of propagation for the writing wave $R_W(\vec{r})$ is normal to the hologram front surface and the reading wave $R_R(\vec{r})$ has a small angle θ of deviation with respect to the writing wave, as shown in Fig.2.

By using the Fresnel-Kirchhoff diffraction integral[10], the writing and reading reference waves in this system can be expressed as

$$R_W(\vec{r}) = \int_{-\infty}^{\infty}P(\vec{r}_0)A_W(\vec{r}_0)h_W(\vec{r},\vec{r}_0)d\vec{r}_0 \tag{6}$$

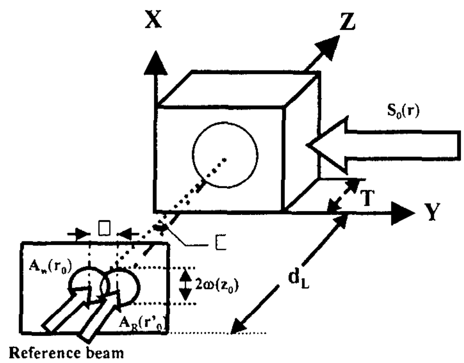

Fig.2. Geometry of the hologram recording by signal plane wave $S_0(r)$ and dynamical speckle reference wave $R_W(r)$ and reading wave $R_R(r)$. Here T is the diameter of signal beam, d_L is the distance from the hologram front surface to random-phase diffuser, Δ is the shift of the illuminated part of the diffuser and θ is an angle between writing beam and reading beam.

$$R_R(\vec{r}') = \int P(\vec{r}_0')A_R(\vec{r}_0')h_R(\vec{r}',\vec{r}_0')d\vec{r}_0' \tag{7}$$

where $\vec{r}$ and $\vec{r}'$ denote the vector coordinate of the diffuse plane, $A_W(\vec{r}_0)$, $A_R(\vec{r}_0')$ are the complex amplitude transmittance of the diffuser with respect to writing and reading waves, respectively. The following relationship is satisfied

$$\left\langle A_W^*(\vec{r}_0)A_R(\vec{r}_0')\right\rangle = \delta\left(\vec{r}_0 - \vec{r}_0' - \vec{\Delta}\right) \tag{8}$$

in which $\delta(\ )$ represents a Dirac delta function, $\langle\cdots\rangle$ standing for an ensemble average and $\vec{\Delta}$ is the shift of the illuminated part of the diffuser arising from the change of incidence angle of illuminating beam.
The transfer functions of the optical system for writing and reading waves can be written

$$h_W(\vec{r},\vec{r}_0) = \frac{1}{i\lambda z}\exp\left(i\frac{2\pi}{\lambda}z\right)\exp\left(i\frac{\pi}{\lambda z}\left|\vec{r}-\vec{r}_0\right|^2\right) \tag{9}$$

$$h_R(\vec{r}',\vec{r}_0') = \frac{\cos\theta}{i\lambda z}\exp\left(i\frac{2\pi}{\lambda}z\right)\exp\left(i\frac{\pi}{\lambda z}\left|\vec{r}'-\vec{r}_0'\right|^2\right) \tag{10}$$

When a Gaussian beam with a waist width ω_0 is employed to illuminate the diffuser, the illumination function of diffuser can be written[11]

$$P(\vec{r}) = \frac{\omega_0}{\omega(z_0)}\exp\left(i\frac{2\pi z_0}{\lambda}\right)\exp\left(-\frac{\left|\vec{r}\right|^2}{\omega^2(z_0)}\right)\exp\left(i\pi\frac{\left|\vec{r}\right|^2}{\lambda\rho(z_0)}\right) \tag{11}$$

where $\omega(z)$ and $\rho(z)$ are the width and wave front curvature radius of the illuminating beam at the diffuser and are given by

$$\omega(z) = \omega_0\left(1 + z^2/a^2\right)^{1/2} \tag{12}$$

$$\rho(z) = z\left(1 + a^2/z^2\right) \tag{13}$$

and

$$a = \pi\omega_0^2/\lambda \tag{14}$$

Substitution of Eqs (6)-(11) into Eq.(5) leads to

$$S(\vec{r}) = Ak_0^2\exp\left(i\vec{k}_{S_0}\cdot\vec{r}\right)\frac{\exp(ikr)}{4\pi r}\int_{-\infty}^{\infty}\Gamma(\vec{r},\vec{r}')dV' \tag{15}$$

where $\Gamma(\vec{r},\vec{r}')$ is the cross-correlation function of the speckle reference beams, given by

$$\Gamma(\vec{r},\vec{r}')=\left\langle R_W^*(\vec{r})R_R(\vec{r}')\right\rangle=\frac{\omega_0^2\cos\theta}{\omega^2(z_0)\lambda^2z^2}\exp\left(-\frac{|\vec{\Delta}|^2}{2\omega^2(z_0)}\right)$$

$$\times\exp\left(-\frac{\pi^2\omega^2(z_0)}{2\lambda^2z^2}\left|\sigma\vec{\Delta}-\vec{r}+\vec{r}'\right|^2\right)\times\exp\left\{i\frac{\pi}{\lambda z}\left[|\vec{r}|^2-|\vec{r}'|^2+\vec{\Delta}\cdot(\vec{r}+\vec{r}')\right]\right\} \tag{16}$$

where $\sigma=1+\frac{z}{\rho(z_0)}$, $|\vec{\Delta}|=d_L tg\theta$.

As the experimentally measured value is the diffracted beam intensity $I_D=|S|^2$, it is convenient to introduce the parameter of relative diffracted beam intensity $I_{DN}(\theta)=I_D(\theta)/I_D(\theta=0)$, where $I_D(\theta=0)$ is the diffracted beam intensity at zero angle deviation. Then we can express the $I_{DN}(\theta)$ as

$$I_{DN}(\theta)=\cos^2\theta\exp\left(\frac{d_L^2tg^2\theta}{\omega^2(z_0)}\right)\frac{\left|\iiint_{V'}H(\vec{r},\vec{r}')\exp[\mathrm{M}(\vec{r},\vec{r}')]\exp[i\mathrm{N}(\vec{r},\vec{r}')]dx'dy'dz'\right|^2}{\left|\iiint_{V'}H(\vec{r},\vec{r}')dx'dy'dz'\right|^2} \tag{17}$$

where

$$H(\vec{r},\vec{r}')=\frac{1}{z^2}\exp\left\{-\frac{\pi^2\omega^2(z_0)}{2\lambda^2z^2}\left[x'^2+(y-y')^2\right]\right\}\exp\left\{i\frac{\pi}{\lambda z}\left[-x'^2+\left(y^2-y'^2\right)\right]\right\}$$

$$\mathrm{M}(\vec{r},\vec{r}')=-\frac{\pi^2\omega^2(z_0)}{2\lambda^2z^2}\left[\sigma^2d_L^2tg^2\theta+2\sigma d_Ltg\theta(y-y')\right]$$

$$\mathrm{N}(\vec{r},\vec{r}')=\frac{\pi}{\lambda z}d_Ltg\theta(y+y')$$

The equation (17) can be used to discuss the storage properties of our novel system, such as, the influence of speckle size on the data storage density. From this equation the speckle size is determined by the $\omega(z_0)$ and d_L, i.e. the correlation length of dynamic speckle $\delta=\frac{\lambda z}{\pi\omega(z_0)}$.

3. EXPERIMENTAL RESULTS

We have calculated numerically the dependence of diffracted beam intensity $I_{DN}(\theta)$ on incident angular deviation at reconstruction with different speckle sizes according to Eq.(17). The speckle size varied with the distance from the front surface of the hologram to random phase diffuser and the diameter of illuminated part on the diffuser. The sensitivity of the diffracted beam $I_{DN}(\theta)$ has a monotonic character and smoothly falls down with increase of the angular deviation around the hologram writing beam, as shown in Fig.3.

Obviously, the bigger the speckle size δ is, the more slowly the diffractive intensity attenuates along with the angular deviation increasing. The angular selectivity of the storage arrangement, as shown in Fig.1b, by using the joint action of the angular-shift variation of the illuminating beam that produce a dynamic speckle on the storage medium, can be more sensitive if an appropriate diffuser be used. The characteristics of selectivity become mainly dependent on the properties of the speckle pattern of the reference beam, that is, speckle size. In comparison with the selectivity determined by cross-correlation between recording and retrieving speckle structures the Bragg selectivity of the original angular multiplexing becomes subsidiary.

A standard 90 degree storage geometry for angular multiplexing was used in the experiment to demonstrate the multiple holograms stored in a same volume with dynamic speckle reference beams with simply an addition of diffuser in the reference optical path. As the angle scanning, a collimated light beam will firstly illuminate the diffuser with different incident angle and position and then transmit through diffuser to form a speckle pattern on the surface of the lithium niobite crystal. The central locations of all speckle patterns are almost at the same point during scanning as in the original angular multiplexing system (Fig.1a). A diode pumped YAG laser (λ=532nm, P~200mW) was used as a coherent light source to record volume holograms with a block of $LiNbO_3$: Fe crystal. A ground glass is used as the diffuser in our experiment and the speckle sizes are changed through adjusting the distance from crystal surface to diffuser d_L.

As seen from Fig.4, the angular selectivity is monotonically increasing with the increasing of d_L. The dependence of selectivity on speckle properties showed in Fig.4 corresponds to the theoretical analysis. This consistency shows that our theoretical model is suitable for describing the characteristic of dynamic speckle holographic storage.

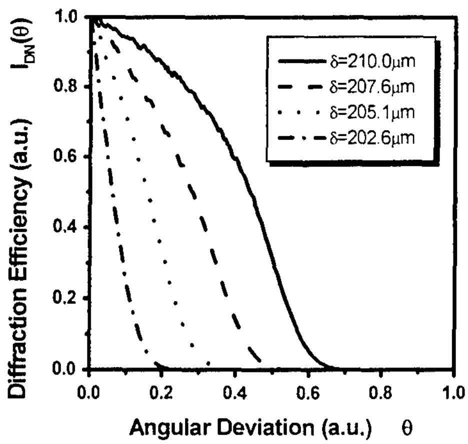

Fig. 3. Calculated dependence of the normalized diffracted beam intensity $I_{DN}(\theta)$ on incident angular deviation θ at reconstruction with different speckle sizes δ. In this case, the parameters of ω_0=370μm, d_L=500mm, and T=8mm are chosen.

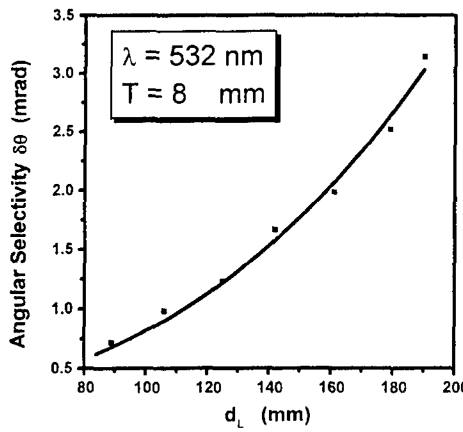

Fig. 4. The incident angular selectivity $\delta\theta$ as a function of the distance d_L from the hologram front surface to random phase diffuser.

4. CONCLUSION

We have proposed a novel scheme that introduces a dynamic speckle in the original angular multiplexing arrangement by means of an appending a random phase diffuser in the front of storage medium along the reference optical path. We have also derived an expression for new angular-shift multiplexing mechanism by applying the perturbation technique and cross-correlation of dynamic speckle as well as the diffractive theory. That calculated results coincide with experimental ones indicates our theoretical model being able to analyze this novel scheme rightly.

The selectivity of holographic storage with dynamic speckle is mainly limited by the speckle size. Reducing the speckle size on the surface of storage medium can unceasingly increase the data storage density as long as the scan resolution meets the needs of retrieval. We can place the diffuser close to the storage medium or change illuminating condition to obtain high-density storage. In addition, the dynamic speckle has ability to achieve 3D holographic storage based on the features of three-dimensional spatial-shift selectivity that leads to get more high-density of holographic storage.

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