Dynamic speckle multiplexing scheme in volume holographic data storage and its realization

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Abstract: Dynamic speckle multiplexing scheme in volume holographic data storage is proposed, since it offers a novel multiplexing geometry, and could be combined with other schemes to make the full use of the dynamic ranges. In this scheme, a random diffuser is added in the original reference path of the classical 90º setup. In this paper, we analyzed the propagation of the speckle field in the holographic system and established the related theoretical model based on the dynamic speckle auto-correlation function and diffraction theory. We successfully realized the dynamic speckle multiplexing in our experimental system and reached a storage density of 4.6 Gigapixels/cm^3 based on the DPL laser source.

OCIS codes: (210.2860) Holographic and volume memories; (030.6140) Speckle

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1. Introduction

Volume holographic data storage is more and more attractive because of its promising high storage density and fast data transfer rate [1]. Holographic multiplexing methods, such as wavelength [2], angular [3], shift [4], and phase encoding [5] have been widely used. These multiplexing methods of volume holograms are based on the selective reconstruction of specific holograms out of an entire ensemble of holograms. However, due to the limitation of the multiplexing methods themselves, none of the methods could exhaust the dynamic range of the storage media entirely. Recently, V. Markov proposed the static speckle multiplexing

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scheme [6, 7], which is based on the spatial autocorrelation character of the speckle field. This scheme permits the real three-dimensional storage and offers a much smaller multiplexing shift. Compared with the conventional plane wave reference beam, it may enhance the storage density greatly.

Unlike V. Markov, we proposed a novel dynamic speckle multiplexing scheme, which generates different speckle fields by moving the random phase diffuser itself, instead of moving the storage crystal. As Fig. 1 shows, we put a random phase diffuser in the reference beam, where, along with the variation of the diffuser, different parts of the diffuser are employed to generate the speckle field. Therefore, the speckle distribution on the surface of the crystal will change. Consequently, the interference of the reference beam and the signal beam will change, finally realizing the optical data storage.

Compared with static speckle multiplexing, in the dynamic speckle multiplexing scheme the storage media will not move during the storage process; therefore, all information is stored in a common volume. This will definitely benefit the storage density of the holographic system. In addition, the dynamic speckle multiplexing scheme can be combined with other schemes, such as angular and spatial multiplexing, to form novel hybrid multiplexing schemes. Later in this paper, we will discuss angular speckle multiplexing and its realization.

In this paper, based on the auto-correlation character of the speckle field and diffraction theory, we establish the theoretical model of the dynamic speckle multiplexing, and discuss the relationship between the correlation length and multiplexing shift. At the end of the paper, we present the experimental result of a high density storage based on dynamic speckle multiplexing, which reaches a storage density of 4.6 Gigapixels/cm^3.

2. Theoretical analysis

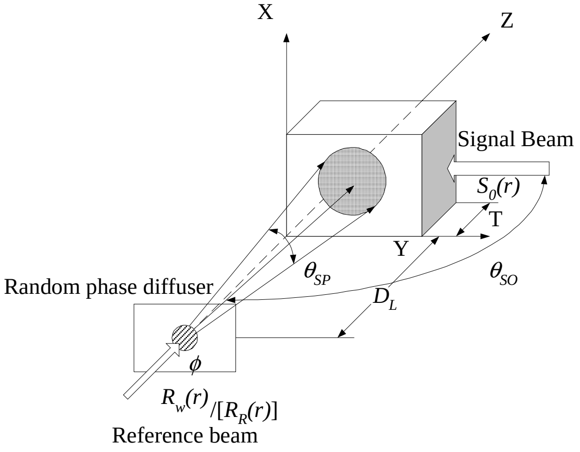

Fig. 1. Geometry of the hologram recording by signal plane wave $S_0(r)$ and dynamical speckle reference wave $R_W(r)$. Here T is the thickness of volume hologram. D_L is the distance from the hologram front surface to random-phase diffuser. Δ is the shift of the diffuser.

As Fig. 1 shows, in the dynamic speckle multiplexing scheme, the speckle-coded reference wave $R_W(\mathbf{r})$ interfere with the plane object wave $S_0(r)=A\exp(ikS_0\bullet\mathbf{r})$, and form the holographic gratings in the storage media. After the exposure, the permittivity of the storage media $\varepsilon(\mathbf{r})$ will change to $\varepsilon(\mathbf{r})=\varepsilon_0+\delta\varepsilon(\mathbf{r})$, where $\delta\varepsilon(\mathbf{r})$ is the modulated component of the permittivity, direct proportion to the square of the electric field of the interacting waves, *i.e.*,

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

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$R_w^*(\vec{r})$ is the conjugate of $R_w(\vec{r})$.

Now, we use the read out speckle encoded field $R_R(\mathbf{r})$ to retrieve the recorded hologram. The retrieve beam $R_R(\mathbf{r})$ and the diffractive beam $S(\mathbf{r})$ could be described by the Maxwell equations. Considering the monochromatic waves of identical polarization in an isotropic media, the Maxwell equation could be reduced to a scalar wave function. With the first Born approximation and perturbation theory method, the diffractive optical field $S(\mathbf{r})$ should be:

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

$G(\vec{r},\vec{r}\,') = \dfrac{\exp\left[ik_0|\vec{r}-\vec{r}\,'|\right]}{4\pi|\vec{r}-\vec{r}\,'|}$ is the Green function.

In the dynamic speckle multiplexing system, when we are multiplexing holograms, the diffuser will move Δ each time. Now, suppose that the retrieve beam $R_R(\mathbf{r})$ is the beam that formed after recording beam $R_W(\mathbf{r})$ moved Δ. And, $R_R(\mathbf{r})$ and $R_W(\mathbf{r})$ propagate in the same direction. Then, according to the Fresnel-Kirchhoff diffractive integration, Eq. (2) could be expressed as,

$$S(\vec{r}) \propto \int_{-\infty}^{\infty} \Gamma(\vec{r},\vec{r}\,') dV' \tag{3}$$

$\Gamma(\vec{r},\vec{r}\,')$ is the mutual correlation function of dynamic speckle field. Generally, we consider only the condition of one dimension movement, i.e., $\Delta=\Delta_y\mathbf{Y}$. Therefore, the mutual correlation function is,

$$\Gamma(\vec{r},\vec{r}\,') = \left\langle R_W^*(\vec{r}) R_R(\vec{r}\,') \right\rangle = \frac{\sqrt{\pi}\,\omega_0^2}{2\sqrt{2}\,\omega(z_0)\lambda^2 z^2} \exp\left(-\frac{\Delta_y^2}{2\omega^2(z_0)}\right) \times \exp\left(-\frac{\pi^2\omega^2(z_0)\Delta_y^2}{2\lambda^2 z^2}\left[1+\frac{z}{\rho(z_0)}\right]^2\right) \times \exp\left(i\frac{2\pi\Delta_y}{\lambda z}y'\right) \tag{4}$$

Use normalized diffractive optical intensity $I_{DN}(\Delta)=I_D(\Delta)/I_D(\Delta=0)$ and the shift of diffuser Δ to describe the multiplexing selectivity of dynamic speckle, where, $I_D(\Delta=0)$ is the diffractive intensity when the diffuser shift is zero, we will get,

$$I_{DN}(\Delta_y) = \exp\left(-\frac{\Delta_y^2}{\omega^2(z_0)}\right) \frac{\left|\iiint_{V'} \frac{1}{z^2} \exp\left(-\frac{\pi^2\omega^2(z_0)\Delta_y^2}{2\lambda^2 z^2}\left[1+\frac{z}{\rho(z_0)}\right]^2\right) \exp\left(i\frac{2\pi\Delta_y}{\lambda z}y'\right) dx'dy'dz\right|^2}{\left|\iiint_{V'} \frac{1}{z^2} dx'dy'dz\right|^2} \tag{5}$$

$\omega(\mathbf{z}_0)$ and $\rho(\mathbf{z}_0)$ are the radius and the curve radius of the illumination beam respectively.

The correlation length of the speckle field on the surface of the storage media is $\delta = 0.66\dfrac{\lambda D_L}{\omega(z_0)}$, D_L is the distance from the diffuser to the surface of the storage media.

3. Computational and experimental results and some discussions

3.1 The relationship between the angular selectivity and the correlation length δ

From the numerical computation Eq. (5), it is possible to discuss the relationship between the diffractive intensity $I_{DN}(\Delta_y)$ and the shift of diffuser Δ_y. The correlation length δ could be adjusted by changing the distance D_L. From the computational results Fig. 2, we could find that, the diffraction intensity will drop monotonically along with the increase of Δ_y. Furthermore, the smaller of the correlation length δ, the faster I_{DN} (Δ_y) drops.

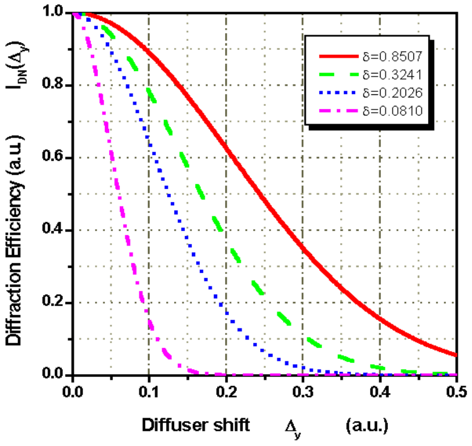

Fig. 2. Calculated dependence of the normalized diffratcted beam intensity I_{DN} (Δ_y) on shift Δ_y at reconstruction with different speckle sizes δ.

In the holographic data storage system, we put a random diffuser before the storage media along the reference optical path.

As we move the motor controller, different parts of the diffuser will be illuminated, and thus, different speckle fields will be generated on the surface of the storage media. We adjust the distance of D_L to get different speckle field with different correlation length δ. We have known that, the smaller of D_L, the smaller of δ. From Fig. 3, it is easy to find that, the smaller of correlation length δ, the better of the multiplexing shift of the dynamic speckle multiplexing system, which bears well accordance with the theoretical analysis.

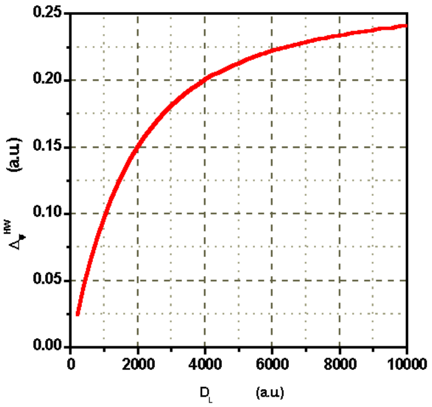

Fig. 3. The shifting selectivity Δ_y^{HW} as a function of the distance D_L from the hologram front surface to random phase diffuser

3.2 High density storage experimental results

The storage system was designed for high-density dynamic speckle multiplexed holographic storage using the 90° geometry. The storage material is Iron Doped Lithium Niobate ($LiNbO_3$:Fe, 0.03% Fe-doped). Light from a frequency-doubled diode pumped Nd:YAG laser was expanded and split into reference and object beams. The reference beam passed the random phase diffuser and was converged to the crystal. 500 digital frames, each curtaining 1024×768 pixels, were successfully stored and retrieved in a common volume of 0.086 cm^3 of

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the storage crystal, reaching the storage density of 4.6 Gagapixels/cm^3. Besides, the crystal was immersed in the NaCl solution to suppress the influence of photovoltaic field and the possible degradation [8].

3.3 The hybrid multiplexing scheme based on dynamic speckle multiplexing

From the theoretical analysis of dynamic speckle multiplexing scheme, we could know that, it could be combined with other multiplexing schemes to get new hybrid multiplexing schemes.

If we put a random diffuser in the original 90° angular multiplexing geometry, then it turns into the dynamic speckle angular multiplexing scheme. Suppose that the retrieve beam $R_R(\mathbf{r})$ is a different speckle field that forms after the recording beam $R_W(\mathbf{r})$ turns a tiny angle $\delta\theta_A$ ($\delta\theta_A << 1$), and they have the same propagation direction, then, the diffraction optical field could be expressed as [9],

$$S(\delta\theta_A,\vec{q}\,') = \exp(\vec{k}_0 \sin\theta_S) t_0^2 \int_0^T \frac{1}{z'\delta\theta_A} \exp\left\{\frac{-ik_0\delta\theta_A}{d_L}\left(z'\delta\theta_A + 2y\right)\right\} J_1\left(\frac{k_0\phi_L\delta\theta_A}{2d_L} z'\right) dz' \quad (6)$$

After normalization, we can get the relation between the multiplexing shift and the deviation angle $\delta\theta_A$ [9],

$$\frac{I_D(\delta\theta_A)}{I_{D\,\max}} = \frac{1}{\pi}\left(\frac{4d_L}{k_0 D_H \phi_L T}\right) \iint_{0\le q^2 \le D_H^2/4} \left|S(\delta\theta_A,\bar{q}')\right|^2 d^2q' \quad (7)$$

$I_{D\max}$ is the readout intensity when the angular deviation is zero.

To prove its validity, we employ it in the real dynamic speckle angular multiplexing storage system. 300 digital frames, each curtaining 1024×768 pixels, were stored in a common volume. Because of the dynamic speckle angular multiplexing scheme is insensitive to the multi-longitudinal mode of DPL [10], the full angle of the system is only 2.28°, which is much smaller compared with the traditional angular scheme which may need the full angle of 13.6°.

4. Conclusion

In this paper, the dynamic speckle multiplexing scheme is proposed to enhance the storage density of a volume holographic data storage system. A theoretical model was proposed, and numerical and experimental results correspond very well with each other, proving the correlation length of the speckle field in the reference beam determines the multiplexing shift, where, the smaller of the length δ, the better the multiplexing selectivity. In addition, a very high storage density of 4.6 Gigapixels/cm^3 was reached based on the dynamic speckle multiplexing in our holographic system. We also realized the hybrid dynamic speckle angular multiplexing scheme experimentally, which has the best potential to realize super-high storage density.

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