Optics Communications 284 (2011) 4408–4411

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Improving longitudinal shifting selectivity of volume holographic optical elements by introducing a light pipe

Ching-Cherng Sun *, Che-Chu Lin, Yeh-Wei Yu, Xuan-Hao Lee, Tun-Chien Teng

Department of Optics and Photonics, National Central University, Chung-Li 320, Taiwan

ARTICLE INFO

Article history:
Received 21 October 2010
Received in revised form 20 May 2011
Accepted 30 May 2011
Available online 14 June 2011

Keywords:
Volume holography
Longitudinal selectivity
Volume holographic optical element

ABSTRACT

We propose a new scheme to enhance the longitudinal Bragg selectivity of a volume hologram with use of a light pipe. Longitudinal shifting selectivity of the system is shown to be obviously enhanced in both experimental measurement and theoretical calculation. Such a technique is not only useful in the volume holographic 3-D imaging but also useful in the shift multiplexing holographic optical storage system.

1. Introduction

Volume holographic optical element (VHOE) attracts attentions due to potential applications in unique functions, for example, 3-D imaging, spatial sensing, wavelength filtering and spatial interconnection [1–13]. The volume holographic 3-D imaging element includes confocal microscopy, multidimensional tomographic imaging and volume holographic telescope. For these imaging elements, the resolution of the image in lateral and longitudinal direction is proportional to the shifting selectivity in lateral and longitudinal direction, respectively. Techniques such as fiber bundles, random phase modulation and spatial filtering have been applied to enhance the lateral shifting selectivity [14–19]. The holographic confocal microscopy has been used widely in the biomedical imaging. It is shown that its longitudinal shifting selectivity can be improved by using objective lens with high numerical aperture (NA) [20–24]. Even so, higher longitudinal shift selectivity is still demanded. In this paper, we propose a novel structure to improve the longitudinal shifting selectivity for spherical reference wave by using a light pipe. The theoretical simulation as well as the corresponding experiment is demonstrated. Such a VHOE can also be combined with the high NA objective lens in application.

2. Principle and simulation

The schematic diagram of the spherical reference wave for the holographic filter is shown in Fig. 1. A divergent spherical wave (E_r) serves as the reference beam and a plane wave (E_s) serves as the signal beam in the writing process. Without considering the refraction of the boundary of the recording medium, the reference beam and the signal beam can be expressed

$$E_r = \frac{A_r \ \exp(ikr_1)}{r_1}, \tag{1}$$

$$E_s = A_s \ \exp(ikx)\delta(y-y_s)\delta(z-z_s), \tag{2}$$

where k is the wave number in the VHOE, (y_s, z_s) is the location of the signal beam, A_r and A_s are the amplitudes of the reference beam and the signal beam, respectively. And r_1 is the distance between the focusing point and the recording medium in the recording process, which can be expressed

$$r_1 = \sqrt{x^2 + y_s^2 + z_s^2}. \tag{3}$$

In the reading process, the reading light can be expressed

$$E_p = \frac{A_p \ \exp(ikr_2)}{r_2}, \tag{4}$$

where A_p is the amplitude of the reading beam, and r_2 is the distance between the point source of the reading wave and the recording medium in the reading process, which can be expressed

$$r_2 = \sqrt{(x + \Delta x)^2 + (y_s + \Delta y)^2 + (z_s + \Delta z)^2}. \tag{5}$$

Δx, Δy, and Δz are the displacements of the reading light with respect to the reference light along x, y and z axes, respectively. The

* Corresponding author. Tel.: +886 3 4685877; fax: +886 4276240.
E-mail address: ccsun@dop.ncu.edu.tw (C.-C. Sun).

0030-4018/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2011.05.076

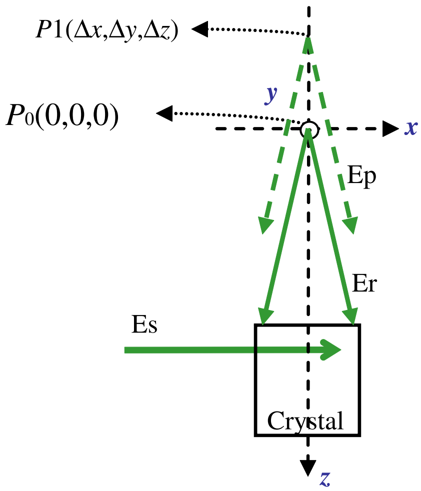

Fig. 1. The schematic diagram of writing process.

most rigorous way to calculate the diffraction of a volume hologram is to use coupled mode theory (CMT). It is, however, not convenient in calculating the property of complex wavefronts. [25,26]. Under weak coupling, Born's approximation as well as VOHIL model (volume hologram being an integrator of the lights emitted from elementary light sources) can effectively increase the calculation speed and does not lose the accuracy [27]. In this paper, all the calculation for volume holography is based on VOHIL, the diffraction light can be expressed as

$$E_d \propto \int_{-w/2}^{w/2} E_p E_r^* E_s \ \exp\left[ik\left(\frac{w}{2}-x\right)\right]dx, \tag{6}$$

where w is the dimension of the VHOE along the diffraction direction, i.e., the x axis. We introduce Eqs. (1–5) to Eq. (6), and the diffraction light can be re-written

$$E_d \propto \int_{-w/2}^{w/2} A_p A_r A_s \frac{\exp[ik(r_2-r_1)]}{r_1 r_2}dx, \tag{7}$$

and the relative diffraction intensity can be obtained

$$I_d \propto \left|\int_{-w/2}^{w/2} A_p A_r A_s \frac{\exp[ik(r_2-r_1)]}{r_1 r_2}dx\right|^2. \tag{8}$$

Eq. (8) shows that the diffraction intensity drops dramatically when the value of position deviation (Δx, Δy or Δz) increases, and we can obtain lateral, vertical and longitudinal shift selectivity of the VHOE through the calculation.

The proposed approach to improve the longitudinal selectivity is to insert a light pipe between the light source of the reading light and the VHOE, as shown in Fig. 2. The light pipe is a rectangular pipe made by four mirrors in the dimensions of $w \times h \times L$, where w, h, and L are the width, height and length of the light pipe, respectively. To build an effective model, we can decompose the reference beam through the pipe into five parts. The reference light is equal to the lights from five point sources with separation distances of $\pm h$ and $\pm w$ in the horizontal and vertical directions, respectively, and can be expressed

$$E_r' = \sum_{i=1}^{5} \frac{A_{ri} \ \exp(ikr_{1i})}{r_{1i}}, \tag{9}$$

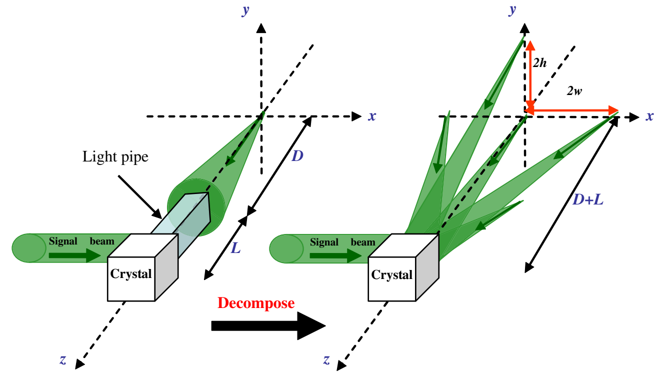

Fig. 2. The schematic diagram of the five spherical waves by introducing a light pipe.

where A_{ri} is the amplitude of the five spherical waves, respectively, and the corresponding distances between the reference light sources and the VHOE is r_{1i}. A plane wave (E_s) along the x-axis is used as the signal beam in the writing process, which is written

$$E_s = A_s \ \exp(-ikx)\delta(y-y_s)\delta(z-z_s). \tag{10}$$

In the reading process, the reading light (E_p') can be expressed

$$E_p' = \sum_{j=1}^{5} \frac{A_{pj} \ \exp\left(ikr_{2j}\right)}{r_{2j}}, \tag{11}$$

where Δx, Δy and Δz are the displacements of the reading light with respect to the reference light along x and y and z axes, respectively. And r_{2j} is the distances between the reference light sources and the VHOE.

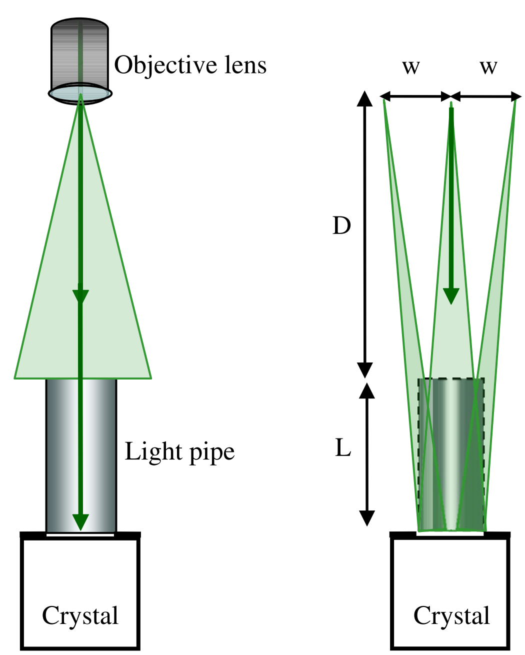

Fig. 3. The schematic diagram of shadow effect of the effective lights by reflection. D is the distance between the focal point of the objective lens and the front side of light pipe, w and L are the width and length of the light pipe, respectively.