第 11 卷 第 5 期
2003 年 10 月
光学 精密工程
Optics and Precision Engineering
Vol. 11 No. 5
Oct. 2003

Article ID 1004-924X(2003)05-0502-06

Optical heterodyne scanning holography

SUN Ping[1,2], XIE Jing-hui[1]

(1. Department of Optical Engineering, Beijing Institute of Technology, Optical Information Processing Laboratory of Ministry of Education, Beijing 100081, *China; 2. Department of Physics, Beijing Normal University, Beijing* 100875, *China)*

Abstract: The theories behind both optical heterodyne scanning holography, a novel 3-D imaging technique, and circular grating optical scanning holography, a holographic technique based on optical heterodyne scanning holography, and its advantages over traditional optical heterodyne scanning holography, are discussed in detail, and some of optical heterodyne scanning holograph's potential applications, including 3-D remote sensing and medical imaging, are presented with typical examples given.

Key words: optical heterodyne scanning holography; Fresnel zone plate; circular grating optical scanning holography; 3-D imaging

CLC number: TB877 **Document code:** A

3-D 成像新技术——光学外差扫描全息术

孙 萍[1,2], **谢敬辉**[1]

(1. **北京理工大学 光电工程系 光学信息处理教育部开放实验室**, **北京** 100081;
2. **北京师范大学 物理系**, **北京** 100875)

摘要:介绍了一种新的 3-D 成像技术—光学外差扫描全息术的基本原理,以及基于光学外差扫描全息术基本原理的环形光栅光学扫描全息术,描述了其与传统的光学外差扫描全息术相比具有的优势。最后,以光学外差扫描全息术在三维空间滤波、遥感和三维混浊液体中成像应用为例,阐述了这一新技术的应用前景。

关 键 词:光学外差扫描全息术;菲涅耳波带板;环形光栅扫描全息术;三维成像

中图分类号:TB877 **文献标识码**:A

1 Introduction

The use of holography to store 3-D optical information is one of the most important aspects from the scientific point of view. Holography has been an important tool for scientific and engineering studies, and it has found a wide range of applications such as in physics, chemistry, biology, medicine, crystallography, electrical engineering, mechanical engineering and other domains[1]. Recently, a newly holographic technique called optical heterodyne scanning holography (OSH) is paid more attentions in 3-D imaging due to its attractive advantages, related to production of holograms of large-scale objects and reduction of the spatial bandwidth[2], incoherent image processing[3], real-time holography imaging and efficient light uti-

Received date: 2003-02-17; **Revised date:** 2003-08-22.

lization[4-5], parallelism of signal processing and reduction of information content[6], simultaneous recognition of 3-D images[7], digital manipulations[8-9], and so on. OSH was first suggested by Poon and Korpel[10] and originally analyzed by Poon[11] using an optical transfer function approach. Afterwards, considering the practical laser beam, Bradley and Poon modified the effective values of pupil function[2]. Then Poon suggested the real-time 2-D holographic imaging by using an electron-beam-addressed spatial light modulator (EBSLM)[4]. He also suggested 3-D microscopy by OSH[12]. In recent years, OSH has been applied in 3-D location of fluorescent inhomogeneities in turbid media[13-15], optical image recognition of 3-D objects[16], 3-D remote target location[8]. In this paper, we first review the basic principle of OSH as a relatively new 3-D imaging technique in Sec. 2. In Sec. 3 we introduce the circular grating optical scanning holography (CGOSH), proposed by Liang and Xie[17-19], based on the basic principle of OSH. In Sec. 4 we present some examples of potential applications of OSH. Finally, we summarize the paper and make remarks in Sec. 5.

2　Principle of optical heterodyne scanning holography

OSH is a technique in which 3-D information of an object can be recorded using heterodyne optical scanning. Corresponding to the principle of holography, the technique also consists of two stages: the recording or coding stage, and the reconstruction or decoding stage.

In the recording stage, the 3-D object is 2-D scanned by a time-dependent Fresnel zone plate (TDFZP)[12]. The TDFZP is created by the superposition of a plane wave and a spherical wave of different temporal frequencies. The situation is shown in Fig. 1. While the object is scanned, a photodetector collects the light transmitted through it (if the object is diffusely reflecting, a photodetector should be used to pick up the scattering light) and delivers a heterodyne scanned current $i_{scan}(x, y)$, as an output. The current, which contains the FZP coded information of the object, is mixed down to become a demodulated signal $i_d(x, y)$. When the demodulated signal is synchronized with the x and y scans of the x-y optical scanning system and fed to a 2-D display, what is displayed (or stored in a computer) in 2-D is a hologram or a FZP coded information of the object being scanned.

Reconstruction of the coded image can be achieved optically by producing a transparency of the coded image, illuminating it with coherent light, and observing the diffraction pattern at some distance z. Mathematically this can be described as multiplying the hologram function by a plane wave and propagating the resulting field using diffraction theory. The propagation of a light wave through free space is equal to a linear operation with the filter response (commonly known as the free-space impulse response). If reconstruction is to be performed numerically, the digitally stored hologram can be convolved with the free-space impulse response at the desired plane of interest z.

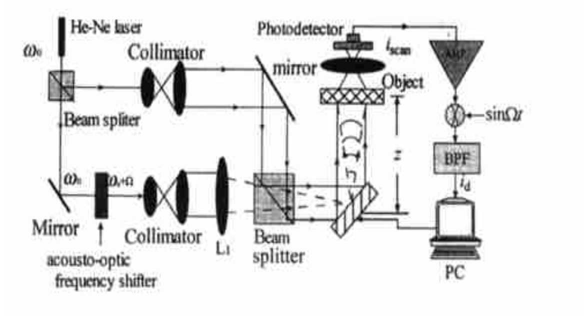

Fig. 1　Optical scanning holographic system

3　Circular grating optical scanning holography

In fact, the reconstruction principle of OSH is based on the fact that the autocorrelation of FZP is a δ function. Numerical calculation shows that, under the condition that both the FZP and the circular grating (CG) have the same aperture size and the CG has a spatial frequency equaling to the maximum frequency of the FZP, the autocorrelation of CG will be closer to a δ function than that of FZP[18]. For a practical FZP, its autocorrelation departs from a (function, because its rings are limited. Since the space between adjacent rings are not spatially uniform for a FZP, while the spacing are uniform for a CG, with the same aperture size and the same spatial resolution, the number of rings of a CG will be more than that of a FZP. So better performance can be predicted if a CG is used as the scanning light field during the recording stage and as the reconstruction function in the second stage.

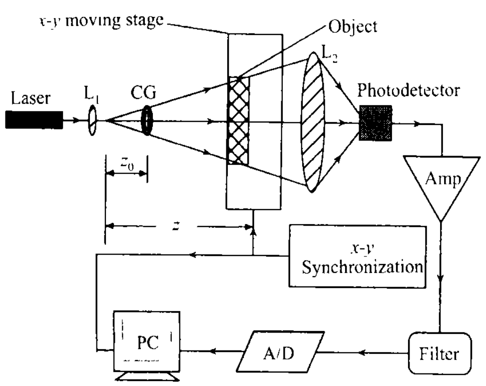

Fig. 2 Practical setup of the circular grating optical scanning holography

Fig. 2 shows a practical setup of the CGOSH. The laser beam is focused on a point source S by lens L_1. A CG, located at a distance z_0 away from this point source, is illuminated by the spherical wave coming from S, and projection images of CG will be generated along the direction of the propagation of light.

Set a coordinate system (x_1, y_1, z), with its origin at S, the transmittance intensity of a CG is given by

$$I_{CG}(x_1, y_1, z_0) = \begin{cases} 1, \text{if} \\ 0, \text{else} \end{cases} \cos\left(\frac{2\pi}{d_0}\sqrt{x_1^2 + y_1^2}\right) \geq 0, \quad (1)$$

where d_0 is the ring spacing of the CG.

According to simple geometry, it can be proved that the intensity distribution of CG projection at a plane $z = z$ is (no consideration of diffraction)

$$I_{CG}(x_1, y_1, z_0) = \begin{cases} 1, \text{if} \\ 0, \text{else} \end{cases} \cos\left(\frac{2\pi z_0}{z d_0}\sqrt{x_1^2 + y_1^2}\right) \geq 0, \quad (2)$$

CGOSH also consists of the recording stage and reconstruction stage and is based on the same principle like the OSH. Mathematically, the recording stage and reconstruction stage are given respectively by

$$H(x, y, z) = O(x, y, z) * I_{CG}, \quad (3)$$

$$\hat{O}(x, y, z) = H(x, y, z) ☆ I_{CG}, \quad (4)$$

Where * denotes the convolution operator and ☆ the correlation operator.

Fig. 3 Practical setup of the circular grating optical scanning holography

4 Potential applications of optical scanning holography

4.1 3-D Coding and decoding, 3-D preprocessing, and 3-D space-variant filtering

In resent years, attempts have been made to improve the contrast of interference fringe pattern in holographic recording. Processing can not only improve the reconstructed image quality but also lead to the reduction of information content to be recorded in the hologram. The optical scanning approach to holographic recording allows us to investigate the possibility of performing real-time preprocessing of the object while its holographic information is recorded, modifying the characteristics of the scanning beam by spatially modulating the laser beams. If a structured beam is used to code the

3-D object, say by modifying the focused beam through a mask in front of lens L1 (as shown in Fig. 1), we have a new 3-D coded object. Hopefully, the way we modify the beam can perform useful processing of the object being scanned.

Fig. 3 is an example by performing computer simulation[6]. By placing a Gaussian annular aperture (a thin ring-aperture with opening of the ring shaped according to a Gaussian function) in the front focal plane of lens L_1, a structured beam is created. Fig. 3(a) shows the original object, Fig. 3(b) shows the reconstruction of the hologram created by FZP scanning, and Fig. 3(c) shows the reconstruction of the hologram in which the hologram has been generated by convolving the structured beam with the object. It is evident that the reconstructed object has been edge-extracted, which means that the hologram contains only the edge information of the object, thereby reducing the information content to be stored in the hologram. This concept provides a powerful coding scheme for holographic recording and also suggests the idea of 3-D space-variant filtering which could be realized by modifying the laser beam while scanning.

4.2 3-D remote sensing

Laser radar is an important type of 3-D imaging systems for remote sensing application. Traditionally, laser radar record 3-D object through a combination of time-of-flight measurement at each 2-D pixel. A new recording technique, based on scanning an object or scene with a complex optical field, originating from a single laser, and collecting the reflected light by use of a photodetector, is proposed[9]. This technique, based on OSH, is similar in operation to a standard laser radar system in which the image is built up pixel by pixel as the laser pattern is scanned over the object.

As the object size increases, the size of FZP scanning field must also be increased. The traditional OSH setup has an inherent disadvantage in this case, because a large collimated beam (acting as the plane wave) is required to generate a large FZP. A diverging FZP field, consisting of the superposition of two spherical waves of different radii of curvature, can solve this problem. According to the practical laser beam, the FZP intensity distribution should be multiplied by a Gaussian function as following[2,9]

$$I_{\mathrm{FZP}} = \exp\left[-\frac{(x^2+y^2)}{\alpha}\right]\cos\left[\frac{k_0}{2z}(x^2+y^2)\right], \quad (5)$$

where α represents the Gaussian roll-off. The reconstruction is based entirely on numerical methods because the hologram exists as a digital image. Fig. 4 shows some experimental results of proof-of-principle.

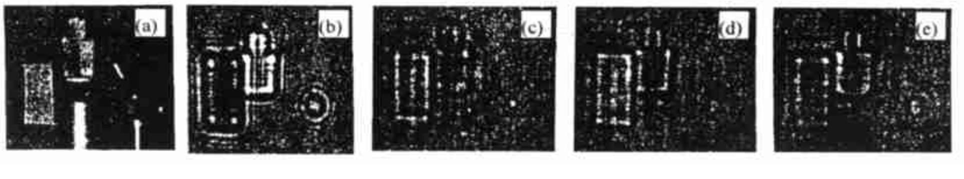

Fig. 4 (a) Original object: a point, a rectangular and a cylindrical object; (b) experimentally recorded hologram; (c), (d) and (e) numerical reconstruction of the rectangular object, the cylindrical object and the point object respectively

4.3 Medical imaging

Optical imaging in turbid media by OSH has potential applications in noninvasive medical diagnosis. The OSH technique utilizes incoherent scanning holography to capture 3-D information in a single 2-D scan. It is an important advantage over other depth slicing or tomographic methods that require multiple 2-D scans. In addition, the method is suited for imaging of fluorescence, absorbing and scattering specimens without the coherent problems of speckle and sensitivity to phase inhomogeneities. The phase-sensitive heterodyne detection serves two critical purposes[13-14]. First, it selects the fluorescence that is due to the ballistic and snake photons of the excitation field, which carry the spatial information of the FZP by multiply scattered light. Next, it eliminates the background buildup that plagues all other incoherent holographic methods. The resulting data are thus a single-side band holographic record free from zero order and twin images[20].

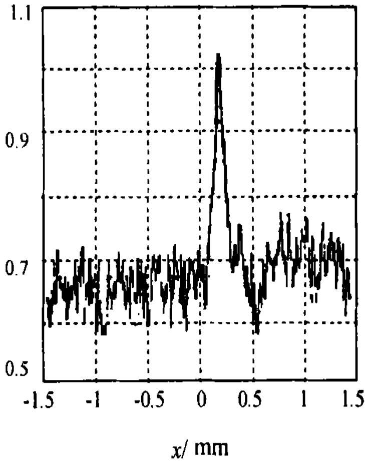

Fig. 5 Reconstruction of a hollow-core optical fiber embeded 30 mm behind the cuvette window with a turbid medium

Fig. 5 shows a reconstruction of a hollow-core optical fiber embedded 30 mm behind the entrance window of a 40-mm-deep cuvette filled with Rhodamine 6G[14]. The turbid medium is a water solution of polystyrene beads (0.18 μm diameter, 0.6 % concentration by volume). This experimental result demonstrates that scanning heterodyne holography offers some possibilities for 3-D imaging in turbid medium like tissue. Besides the above examples, OSH also has other applications such as in holographic TV, 3-D microscopy, optical correlators, optical image recognition, real-time image processing, etc.

5 Summary

We have reviewed a new holography recording technique in which 3-D information of an object can be achieved with 2-D optical scanning, called OSH. First, We have given the basic principle of OSH. OSH is based on scanning the object with a temporally modulated FZP which is generated by superposing a plane wave with a spherical wave from the same laser. The hologram of object is achieved by the convolution between the optical field of FZP and the intensity distribution of the object. Usually, the reconstruction of the image is performed digitally. The object can be reconstructed by the convolution between the optical field of FZP, or the free-space impulse response and the hologram. In fact, any pattern that has a sharp autocorrelation (in three dimensions) would be a scanning light field.

Secondly, We have introduced a developed OSH, called CGOSH which is based on the fact that the autocorrelation of a CG is closer to a δ function than that of a FZP. Because the recording and reconstruction are achieved by the convolution operation of the intensity, the projection light source could be incoherent. This is an important advantage of the CGOSH system. Another advantage is that the single light beam is used to record the hologram, so the system becomes more stable. The more important is, in the CGOSH system, a CG is used to substitute a FZP as the scanning light field, hence the resolution power will be improved.

Finally, We have given some examples of potential applications of OSH technique. OSH technique , coupling the advantages of optics and electronics , is simple and powerful for 3-D imaging. It awaits broader applications.

参考文献:

[1] CAULFIELD H J , LU S. *The application of holography* [M]. New York: Wiely ,1970.
[2] BRADLEY D D , POON T C. Gaussian beam analysis of optical scanning holography[J]. *J Opt Soc Am A* , 1992 ,9(2) :229-236.
[3] INDEBETOUW G, POON T C. Novel approaches of incoherent image processing with emphasis on scanning methods [J]. *Opt Eng* , 1992 ,31(10) :2159-2167.
[4] POON T C , SCHILLING W , WU M H , *et al*. Real-time two-dimensional holographic imaging by using an electron-beam-addressed spatial light modulator[J]. *Opt Lett* , 1993 ,18(1) :63-65.
[5] SCHILLING B W , POON T C. Real-time preprocessing of holographic information[J]. *Opt Eng* , 1995 ,34 :3174-3179.
[6] POON T C , WU M H , SHINODA K, *et al*. Optical scanning holography[J]. *Proc IEEE* , 1996 ,84(5) :753-764.
[7] INDEBETOUW G, KLYSUBUN G, KIM T , *et al* , Imaging properties of scanning holography microscopy[J]. *J Opt Soc Am A* , 2000 ,17(3) :380-390.
[8] KLYSUBUN P , INDEBETOUW G, KIM T , *et al*. Accuracy of three-dimensional remote target location using scanning holographic correlation[J]. *Opt Comm* , 2000 ,184 :357-366.
[9] SCHILLING B W , TEMPLETON C. Three-dimensional remote sensing by optical scanning holography[J]. *Appl Opt* , 2001 ,40(30) :5474-5481.
[10] POON T C , KORPEL. Optical transfer function of an acousto-optic heterodyning image processor[J]. *Opt Lett* , 1979 , 4 :317-319.
[11] POON T C. Scanning holography and two-dimensional image processing by acousto-optic two-pupil synthesis[J]. *J Opt Soc Am A* , 1985 ,2(4) :521-527.
[12] POON T C , SCHILLING B W , DOH K B , *et al*. Three dimensional microscopy by optical scanning holography[J]. *Opt Eng* , 1995 ,34(5) :1338-1344.
[13] SCHILLING B W , POON T C , INDEBETOUW G, *et al*. Three-dimensional holographic fluorescence microscopy[J]. *Opt Lett* , 1997 ,22(19) :1506-1508.
[14] INDEBETOUW G, KIM T , POON T-C , *et al*. Three-dimensional location of fluorescent in homogeneities in turbid media by scanning heterodyne holography[J]. *Opt Lett* , 1998 ,23(2) :135-137.
[15] SCHILLING B W. Three-dimensional fluorescence microscopy by optical scanning holography[D]. Ph. D. dissertation , Bradley Department of Electrical Engineering , Virginia Polytechnic Institute and State University , Blacksburg , Virginia , 1997.
[16] POON T C , KIM T. Optical image recognition of three-dimensional objects[J]. *Appl Opt* , 1999 ,38(2) :370-381.
[17] LIANG W G, LIU S , XIE J H , *et al*. Circular grating optical scanning holography[J]. *SPIE* , 2000 ,3951 :54-60.
[18] LIANG W G. Theoretical and experimental investigation on optical scanning holography[D]. Ph. D. dissertation (in Chinese) , Department of optical engineering ,Beijing Institute of Technology ,China , 1998.
[19] LIANG W G, ZHAO D Z , XIE J H , *et al*. OTF and PSF of optical scanning holography[J]. *SPIE* , 1998 ,3553 :239-246.
[20] POON T C , KIM T , INDEBETOUW G, *et al*. Twin-image elimination experiments for three-dimensional images in optical scanning holography[J]. *Opt Lett* , 2000 , 25(4) :215-217.

作者简介:**孙 萍**(1963 -) ,**女 ,吉林长春人 ,北京理工大学在职博士研究生 ,高级工程师 ,研究方向为光学信息处理、薄膜光学。**