第 44 卷第 3 期 光 子 学 报 Vol. 44 No. 3
2015 年 3 月 ACTA PHOTONICA SINICA March 2015

**doi**:10.3788/gzxb20154403.0309003

# 全息波导显示构型设计

刘玉杰[1,2],丁全心[2],李文强[2],闫占军[2]
(1 光电控制技术重点实验室,河南 洛阳,471009)
(2 洛阳电光设备研究所,河南 洛阳 471009)

**摘　要**:针对全息波导显示系统中输入光栅、转折光栅和输出光栅的光栅参量不一致,导致系统设计和光栅制作难度增大的问题.对比正常配置和锥形配置下的光栅方程,可得全息波导显示系统中全息光栅具有相同周期需要满足转向光栅60°锥形配置.由此提出波导侧面装有反射镜的三光栅单波导板显示构型,其中三个光栅周期完全相同,输入光栅和转向光栅条纹走向一致.使用光学设计软件 CODE V 对该构型进行仿真,验证了该构型的可行性.与传统全息波导显示构型相比,侧面反射镜的光路折叠作用使得该构型系统无效显示面积和耦合效率损失减小;三个光栅周期相同且输入光栅和转向光栅条纹走向一致,可以降低系统设计和全息光栅制作难度.该构型可以用于虚拟现实显示或者头戴式显示.

**关键词**:全息波导;衍射光栅;构型设计;体全息;虚拟显示;头戴式显示;平视显示
**中图分类号**:O438.1;O439　　**文献标识码**:A　　**文章编号**:1004-421(2015)03-0309003-5

# Design of Waveguide Holographic Configuration for Display

LIU Yu-jie[1,2], DING Quan-xin[2], LI Wen-qiang[2], YAN Zhan-jun[2]
(1 *Science and Technology on Electro-Optical Control Laboratory*, *Luoyang*, *Henan* 471009, *China*)
(2 *Luoyang Institute of Electro-Optical Equipment*, *AVIC*, *Luoyang*, *Henan* 471009, *China*)

**Abstract**: In a holographic waveguide display system, the inconformity of grating parameters of input grating, turning grating and output leads to a lot of difficulties in system design and gratings fabrication process. The main condition that the turning grating should be in 60° conical mounting, on which all the gratings in a waveguide holographic display configuration have uniform grating periods, was presented by comparing the grating equations in normal mounting and conical mounting. Under this condition, a novel efficient display was proposed by using a waveguide holographic configuration with three holographic gratings of the same grating periods recorded on a single substrate and a reflector placed on the side face of the substrate. The validity of this configuration was proved by the simulation carried out by the optical design software CODE V. The coupling efficiency loss and invalid area can be dramatically reduced by the reflector on the side face, compared with the traditional configuration. Moreover, the complexity of system design and holographic manufacture can be decreased because all gratings used in the proposed design have uniform grating periods and two of them have uniform orientation. The configuration can be applied to virtual reality display or wearable display.

**Key words**: Holographic waveguide; Diffraction grating; Configuration design; Volume hologram; Virtual reality display; Wearable display; Head up display
**OCIS Codes**: 090.2870; 090.1970; 090.7330; 220.4830

---

**Foundation item**: Chinese Aviation Fund (No. 20135169016)

**First author**: LIU Yu-jie(1989－), male, M. S. degree candidate, mainly focuses on holographic display. Email:yujieliu@live.com

**Supervisor**: DING Quan-xin (1958－), male, professor, Ph. D. degree, mainly focuses on digital optical information processing and digital holography. Email:dingqx@163.com

**Received**: Sep. 2, 2014; **Accepted**: Nov. 27, 2014

# 0 Introduction

With the continuous and rapid development of integration optics and microelectronics, the Waveguide Holographic (WGH) technology can be applied widely in image display[1-3], beam expander[4], compact beam illumination[5], compact holographic printer[6], and some other applications. The main advantages of WGH are compact structure, light weight, high efficiency and having compatibility with integrated optical and microelectronics technology[7]. Traditional display system applies off-axis method to display images that need complex lenses, heavy and occupying too much space[8-10]. For this reason, WGH technology is the important technical development trend for a new generation display system. Cameron provided a WGH display system by using a waveguide bar and plate to extend a two-dimensional size of an eyebox[11]. The configuration allowed for a see-through image with a simultaneous bright view of the outside world. However, the utilizing efficiency may be affected by double waveguide coupling, and assembly is difficult. Eisen et al. presented a planar light-guided projection display configuration, in which three Holographic Gratings (HGs) are recorded on a single transparent planar substrate[12]. However, the configuration needs the input display source to be located close to the corner of the planar substrate, which may increase invalid area. Yan et al. proposed a WGH display configuration with double Total Internal Reflection (TIR) HGs in conical mounting and double volume holograms in classical mounting[13]. In this configuration, the overall increase in the number of HGs may increase the complexity of system design and the manufacture steps of HGs. Also, the period of turning HG is different from other two HGs in the later two configurations.

In this paper, a novel display is proposed by using a WGH configuration with a reflector placed on the side face of the substrate and three gratings with the same grating periods. The configuration has the properties of low efficiency loss by using a single substrate and small invalid area by using a reflector. Moreover, the complexity of system design and holographic manufacture can be reduced because all HGs used in this design have uniform grating periods and two of them have uniform orientation direction. The description and principles of this system are discussed and simulation results are demonstrated. The configuration can be applied to virtual reality display or wearable display.

# 1 Basic principles and geometry

The basic WGH configuration is schematically presented in Fig. 1[12]. $H_1$, $H_2$ and $H_3$ are separately input grating, turning grating and output grating. As we can see, it comprises three HGs of different sizes and geometry, all recorded on a single transparent substrate. The first input HG $H_1$ couples the incident light from the display source into the substrate, traps it by TIR, and directs it toward the second HG $H_2$, which expands the light along one direction. After several reflections inside the substrate, the coupled beam reaches $H_2$, where it is redirected toward the much larger third output HG $H_3$, which expands light in the other orthogonal direction and decouples it from the substrate outward toward the viewer.

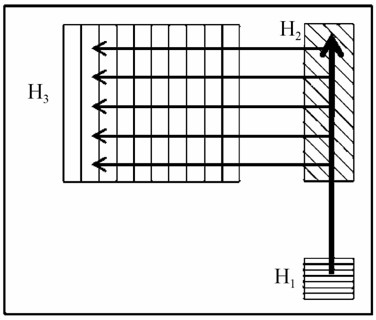

Fig. 1 The basic WGH configuration

Conventionally, the input HG $H_1$ and output HG $H_3$ are in classical mounting. In such classical mounting, the grating vector and the diffraction light lie in the plane of incidence. However, the turning HG $H_2$ is a TIR diffraction grating in conical mounting, where the plane of incidence does not contain the grating vector. Almost all feasible configurations do not add phase, other than multiple integers of $\lambda$, to an incoming beam. For this reason, the grating functions of these HGs are generally satisfied with the following equation

$$\Phi_1+\Phi_2+\Phi_3=C \qquad (1)$$

$\Phi_1$, $\Phi_2$, $\Phi_3$ and $C$ are grating functions of $H_1$, $H_2$, $H_3$ and constant (typically 0) respectively. Furthermore, Eq. (1) is valid for all wavelengths, so the overall optical configuration will have no chromatic dispersion and is therefore appropriate for the polychromatic light. Typically, the output light emerges in a direction either the same as or opposite of that of the incoming light.

# 2 Theoretical analysis of HGs

## 2.1 Input and output HGs

According to the equation of gratings in classical mounting[14]

$$n_{\mathrm{inc}}\sin(\theta_{\mathrm{inc}}) \pm n_{\mathrm{diff}}\sin(\theta_{\mathrm{dif}}) = \lambda/\Lambda \tag{2}$$

where "+" indicates that $\theta_{\mathrm{inc}}$ and $\theta_{\mathrm{diff}}$ are on the same side of the grating normal, and "−" indicates that $\theta_{\mathrm{inc}}$ and $\theta_{\mathrm{diff}}$ are on a different side of the grating normal. Here we assume that the incident light from the air is perpendicular incident upon the substrate and coupled out perpendicularly from the substrate by the output HG, in other words, the incident angle $\theta_{\mathrm{inc},1}$ of input grating $H_1$ and diffraction angle $\theta_{\mathrm{dif},3}$ of the output grating $H_3$ are all zero. Then, the grating period of $H_1$ has

$$\Lambda_1 = \frac{\lambda}{n_{\mathrm{sub}}\sin(\theta_{\mathrm{dif},1})} \tag{3}$$

where $\theta_{\mathrm{dif},1}$ is the diffraction angle of $H_1$ and equals to the transmission angle in the substrate, which should be no larger than the TIR angle. As a result of TIR, the diffraction angle of $H_1$ is equal to the incident angle at $H_2$, and the diffraction angle of $H_2$ is equal to the incident angle at $H_3$. Then the grating period of $H_3$ has

$$\Lambda_3 = \frac{\lambda}{n_{\mathrm{sub}}\sin(\theta_{\mathrm{inc},3})} \tag{4}$$

where $\theta_{\mathrm{inc},3}$ is the incident angle of $H_3$ and is satisfied with the relation $\theta_{\mathrm{inc},3} = \theta_{\mathrm{dif},2}$.

### 2.2 Turning HGs

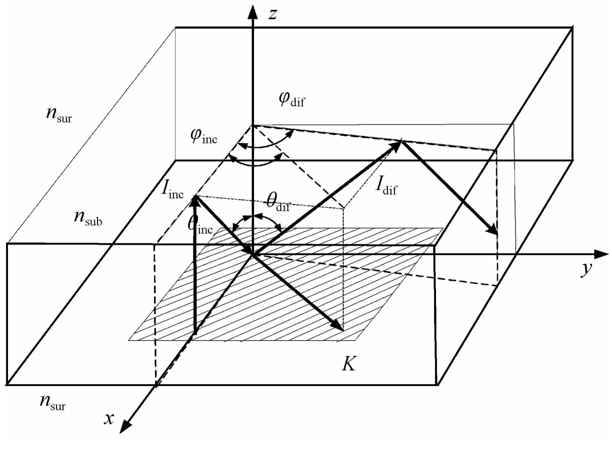

Fig. 2 TIR holographic grating in conical mounting

A typical three-dimensional conical diffraction geometry for TIR diffraction gratings is schematically presented in Fig. 2. The holographic grating is recorded on a transparent substrate of refractive index $n_{\mathrm{sub}}$ that is surrounded with a material (typically air) of refractive index $n_{\mathrm{sur}}$, where $n_{\mathrm{sub}} > n_{\mathrm{sur}}$. A linearly polarized monochromatic light beam, propagating inside the substrate, is obliquely incident onto the TIR holographic grating at the polar angle $\theta_{\mathrm{inc}}$ with azimuthal angle $\varphi_{\mathrm{inc}}$, then diffracted in angle $\theta_{\mathrm{dif}}$ with azimuthal angle $\varphi_{\mathrm{dif}}$. In a WGH display system, we should consider a specific example of TIR diffraction grating in conical mounting, where the polar diffraction angle $\theta_{\mathrm{inc}}$ equals that of the incidence angle $\theta_{\mathrm{dif}}$. The grating period of the turning HG $H_2$[15] has

$$\Lambda_2 = \frac{\lambda\cos(\varphi_{\mathrm{inc},2})}{n_{\mathrm{sub}}\sin(\theta_{\mathrm{inc},2})(1+\cos(\varphi_{\mathrm{dif},2}))} = \frac{\lambda\sin(\varphi_{\mathrm{inc},2})}{n_{\mathrm{sub}}\sin(\theta_{\mathrm{inc},2})\sin(\varphi_{\mathrm{dif},2})} \tag{5}$$

According to Eq. (5), the azimuthal diffraction angle is the twice that of the incident angle

$$\varphi_{\mathrm{dif},2} = 2\varphi_{\mathrm{inc},2} \tag{6}$$

Plug the relation Eq. (6) into the formula Eq. (5), we can carry out the formulation

$$\Lambda_2 = \frac{\lambda\cos(\varphi_{\mathrm{inc},2})}{n_{\mathrm{sub}}\sin(\theta_{\mathrm{inc},2})\sin(2\varphi_{\mathrm{inc},2})} = \frac{\lambda}{2n_{\mathrm{sub}}\sin(\varphi_{\mathrm{inc},2})\cos(\varphi_{\mathrm{inc},2})} \tag{6}$$

when designing the HGs in the WGH configurations, it is necessary to take into account the grating period, which is an important parameter of a diffraction grating and determine the diffraction direction directly. In order to reduce the complexity of design and manufacture, it's better to ensure that the grating periods of all gratings used in a system keep the same value.

For $H_1$ and $H_3$, the same grating periods means $\Lambda_1 = \Lambda_3$. From Eq. (3) and Eq. (4), we can get the relation $\theta_{\mathrm{inc},3} = \theta_{\mathrm{dif},1}$. For $H_1$ and $H_2$, the same grating periods means $\Lambda_1 = \Lambda_2$. From Eq. (3) and Eq. (7), with $\theta_{\mathrm{inc},2} = \theta_{\mathrm{dif},1}$, we can get the equation $2\cos(\varphi_{\mathrm{inc},2}) = 1$. Combining the relation equations above, the condition that all have the same grating periods is $\varphi_{\mathrm{inc},2} = \pi/3$. In other words, the turning grating $H_2$ should be in 60° conical mounting.

## 3 Configuration of WGH display

An overall block diagram of the WGH virtual display configuration is designed by using three HGs, shown in Fig. 3, and the layout of all three HGs is also given and will be clarified in this figure. The structure comprises a reflector located on the side face of the substrate and three HGs of uniform grating period recorded on a single transparent substrate. The input HG $H_1$ and output HG $H_3$ are HGs in classical mounting. $H_2$ is a TIR HG in 60° conical mounting and has the same orientation direction with $H_1$ as shown in Fig. 3.

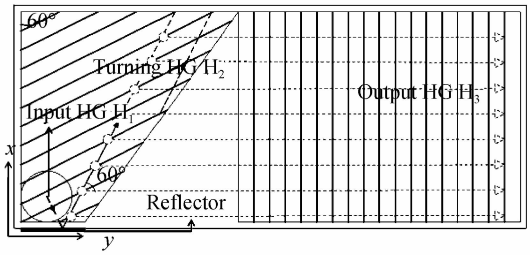

Fig. 3 The layout of WGH display configuration

$\Phi_1$ is the grating phase function of $H_1$

$$\Phi_1=\frac{\sqrt{3}}{2}\frac{2\pi}{\lambda}n\sin(\theta)x+\frac{1}{2}\frac{2\pi}{\lambda}n\sin(\theta)y \tag{8}$$

$\Phi_2$ is the grating phase function of $H_2$

$$\Phi_2=\frac{\sqrt{3}}{2}\frac{2\pi}{\lambda}n\sin(\theta)x+\frac{1}{2}\frac{2\pi}{\lambda}n\sin(\theta)y \tag{9}$$

$\Phi_3$ is the grating phase function of $H_3$

$$\Phi_3=-\frac{2\pi}{\lambda}n\sin(\theta)y \tag{10}$$

$\Phi_r$ is the phase function of the reflector $H_r$

$$\Phi_r=-\frac{2\sqrt{3}\pi}{\lambda}n\sin(\theta)x \tag{11}$$

Where $\theta$, $x$ and $y$ are the diffraction angle, coordinate on the $x$-axis and on the $y$-axis respectively. Also we can get the relation $\Phi_1=\Phi_2$ from Eq. (8) and Eq. (9). The equation means that the two HGs have the same grating periods and orientation. It is worth mentioning that the reflector $H_r$ add constant phase shift on the x-axis only. Combining Eqs. (8)-(11) together, we can get

$$\Phi_1+\Phi_2+\Phi_3+\Phi_r=0 \tag{12}$$

Eq. (12) indicates that our configuration meets the chromatic dispersion equation Eq. (1). Although the single diffraction element produces chromatic dispersion, the total configuration does not add phase shift for all wavelengths, which indicates that the output direction of incident light propagation is consistent with the incoming light. The final output direction of the same polychrome light will be kept identical. Therefore, there are no chromatic problems and appropriate for multi wavelength light display.

The optical system simulation of our WGH configuration is shown in Fig. 4. As we can see from the 3D viewing, the incident beam is diffracted by $H_1$ to the reflector and directed to $H_2$ then. The turning grating $H_2$ expand the beam in a direction which is inclined at an angle of 60° to the y-axis and turn the image-bearing light to $H_3$. At last, the output grating $H_3$ expand the beam in the y-dimension and diffract the beam out to the viewer for display at the same time.

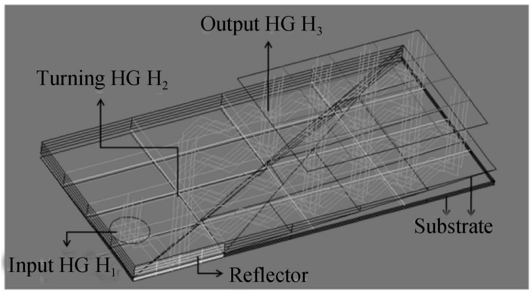

Fig. 4 Simulation result by CODE V

Considering a WGH configuration with no reflector, in order to meet the chromatic dispersion equation Eq. (1), $\Phi_1$ should not be equal to $\Phi_2$

$$\Phi_2=-\Phi_1-\Phi_3=-\frac{\sqrt{3}}{2}\frac{2\pi}{\lambda}n\sin(\theta)x+\frac{1}{2}\frac{2\pi}{\lambda}n\sin(\theta)y \tag{13}$$

The equation means that the $H_1$ and $H_2$ have different orientation, although they have the same grating periods. The orientation of $H_1$ and $H_2$ is symmetric respect to $x$-axis. Then the WGH configuration with no reflector would increase the $x$-axis length of the structure.

Compared with the configuration shown in Fig. 1 and the structure with no reflector analyzed above, our structure is more efficient and economical in space as the result of the additional reflector. Also, the unification of grating periods of all three HGs used in our structure can result in the removal of the production steps and design procedure. All in all, the configuration is efficient in coupling efficiency with a single waveguide, economical in space with the reflector, and easily to be designed and produced with the uniformity of gratings.

## 4 Conclusion

The WGH configuration has advantages of compact structure, light weight, high efficiency and small size. We obtain the main condition, on which all the gratings used in a WGH display configuration have the same grating periods, through theoretical analysis. Based on this condition, we designed a novel WGH display configuration with three HGs of the same grating periods recorded on a single substrate and a reflector placed on the side face of the substrate. By this design, the efficiency loss and invalid area can be dramatically reduced. Moreover, the complexity of system design and holographic manufacture can be decreased because all gratings used in this design have uniform grating periods and two of them have uniform orientation direction. The analysis and simulation results of this system are also presented. The configuration can be applied to virtual reality display or wearable display.

**References**

[1] HOMANM. The use of optical waveguides in Head Up Display (HUD) appications[C]. SPIE, 2013, **8736**: 87360E.

[2] SHECHTER R, AMITAI Y, FRIESEM A A, *et al*. Planar holographic configuration for efficient imaging [J]. *Optics Communications*, 1996, **132**: 221-226.

[3] YOU Meng, HUANG Zhan-hua, CAI Huai-yu. Numerical analysis of the buried parallelogramic grating [J]. *Acta Photonica Sinica*, 2012, **41**(11): 1292-1296.

[4] SHECHTER R, AMITAI Y, FRIESEM A A, *et al*. Compact beam expander with linear gratings [J]. *Applied Optics*, 2002, **41**(7): 1236-1240.

[5] SHECHTER R, BOKOR N, AMITAI Y, *et al*. Compact red-green-blue beam illuminator and expander [J]. *Applied Optics*, 2002, **41**(7): 1229-1235.

[6] PYUN K P, CHOI C, MOROZOV A V, *et al*. Compact

holographic printer using RGB waveguide holographic optical elements[C]. SPIE, 2013, **8616**: 86160R.

[7] PUTILIN A, GUSTOMIASOV I. Application of holographic elements in displays and planar illuminators[C]. SPIE, 2007, **6637**: 66370N.

[8] WU Hai-qing, WANG Xue-na, SUN Qiang, *et al*. Design of refractive/diffractive plastic optical system in head mounted display[J]. *Acta Photonica Sinica*, 2009, **38**(9): 2243-2246.

[9] ZHANG Hui-juan. Optical system design of binocular head-mounted projective display with wide-field-of view[J]. *Acta Photonica Sinica*, 2007, **36**(7): 1264-1267.

[10] YANG Bo, WEI Xiao-na, ZHANG Wei, *et al*. Design method of a free-form HMD system with large pupil size[J]. *Acta Photonica Sinica*, 2011, **40**(7): 1051-1054.

[11] CAMERON A. Waveguide technology & its application in head mounted displays[C]. SPIE, 2012, **8383**: 83830E.

[12] EISEN L, MEYKLYAR M, GOLUB M, *et al*. Planar configuration for image projection[J]. *Applied Optics*, 2006, **45**(17): 4005-4011.

[13] YAN Zhan-jun, LI Wen-qiang, ZHOU Yong-jun, *et al*. Virtual display design using waveguide hologram in conical mounting configuration[J]. *Optical Engineering*, 2011, **50**(9): 094001.

[14] LOEWEN E G. Diffraction gratings and applications[M]. New York: Marcel Dekker INC, 1997.

[15] EISEN L, GOLUB M A, FRIESEM A A. Total internal reflection diffraction grating in conical mounting[J]. *Optics Communications*, 2006, **261**: 13-18.