IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 11, Number 1, February 2019

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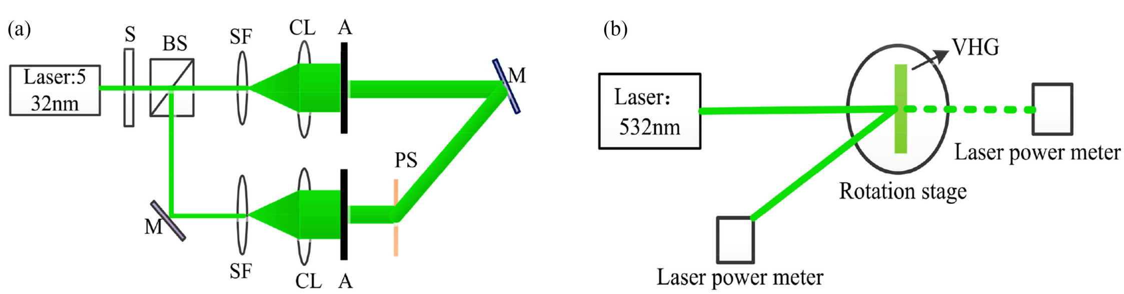

DOI: 10.1109/JPHOT.2018.2889334

Diffraction Efficiency Enhanced Volume Holographic Gratings via Coupling Ag Thin Film

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DOI:10.1109/JPHOT.2018.2889334

Manuscript received November 22, 2018; revised December 15, 2018; accepted December 19, 2018. Date of publication January 2, 2019; date of current version January 22, 2019. This work was supported by the National Natural Science Foundation Project of China under Grant 61571124. Corresponding author: Zhuoya Zhu (e-mail: zzy@seu.edu.cn).

Abstract: Volume holographic gratings (VHGs) act as an in-coupler or out-coupler could be applied in holographic waveguide display system in which high diffraction efficiency is one of the key factors. Here, VHGs coupled with Ag thin film to enhance its diffraction efficiency is demonstrated. The first-order diffraction efficiency of the Ag coupled VHG increases by 34% when the uncoupled VHG is 42.8%. Numerical simulation results demonstrated that the Ag thin film could decrease the forward diffraction, corresponding with the first-order diffraction increasing in the coupled VHG. This paper provides useful information that Ag coupled VHGs may improve the diffraction efficiency of waveguide used in the head-mounted and near-eye display.

Index Terms: Display materials, holography.

1. Introduction

Recently, holographic waveguide display technology has been applied in helmet-mounted display due to its superior size and weight compared with classical head-up display technology [1], [2]. In order to transmit lights in holographic waveguide display, volume holographic gratings (VHGs) are introduced to control the direction of lights propagation. Unlike other traditional binary gratings, refractive index changing periodically in the VHG is the key to achieve light diffraction. Moreover, VHGs with uniform dispersion and low noise are expected to be in-coupled and out-coupled gratings in holographic waveguide display [3], [4], where the luminance of the light transmitting in the waveguide is dependent on the diffraction efficiency of the VHGs.

As known, a reflection VHG is fabricated by two relevant beams incident in the recording materials oppositely. For a reflection VHG, the diffraction efficiency is defined to be

$$\eta = th^2 \frac{\pi \Delta nd}{2n\Lambda \sin^2 \theta} \tag{1}$$

Where d is the thickness of the recording material, n is the refraction index of the medium, Λ is the period of the grating, Δn is the amplitude of the refractive index modulation, θ is the Bragg angle. Diffraction efficiency of the grating may reach 100% theoretically when the product of Δn and d is large enough. However, Δn is limited by the recording materials, and the optical shrinkage

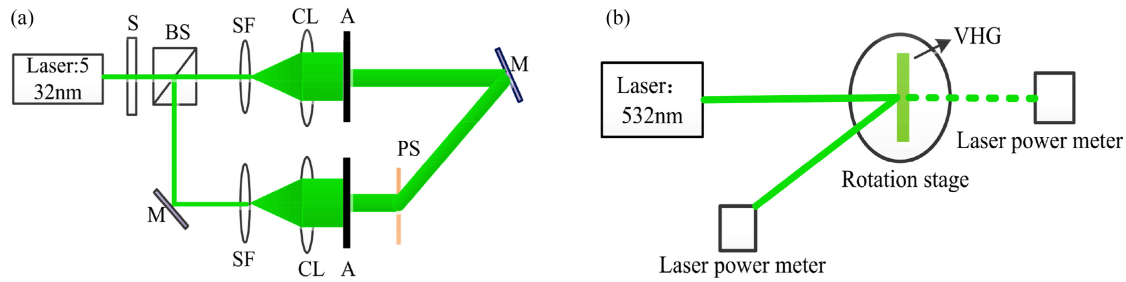

Fig. 1. (a) Experimental setup for recording reflection VHGs, S: shutter, BS: beam splitter, SF: spatial filter, CL: collimating lens, A: aperture, M: mirror, and PS: photopolymer sample. (b) Schematic of measurement for diffraction efficiency of VHG.

of the materials would cause distortion of the VHG during the exposure process when d is large. As a result, many researchers focus on the diffraction efficiency enhancement by matching suitable Δn and d of the reflection VHG. Manivannan *et al.* developed a Fe3+ doped recording system that exhibited a peak diffraction efficiency of 80% [5]. C. Sudha Kartha *et al.* coupled Ag+ in the recording photopolymer before recording and the peak diffraction efficiency reached 75% [6]. However, those most of the metal-ion-doped photopolymer systems are complicated and require high exposure energy consider of their poor energy sensitivity. Furthermore, since the metal-ion-doped system requires no post processing steps, the stability of its diffraction efficiency is the main challenge in contrast with that of conventional photopolymer-based VHGs.

In this work, we proposed the implementation of the Ag thin film coupled VHG. We take advantage of the benefits of photopolymer to design a grating that has moderate energy sensitivity, and that is also stabilized by the UV post processing and the thermal treatment. The structure employs the Ag thin film evaporated on the surface of recorded VHGs, to enhance the first order diffraction efficiency with forward diffraction waves being decreased. A numerical simulation for our VHG has also been achieved and the maximum diffraction efficiency in this work reaches 86% in experiment.

2. Experimental Details

A commercial photopolymer is chosen to be recording material for fabrication of VHGs. The prepared photopolymer solution in which polyvinyl alcohol as the binder matrix, acrylamide as the monomer, Erythrosine B dye and triethanolamine as the photoinitiation system is spin-coated evenly on a 50 mm $\times$ 50 mm glass substrate, then dried in darkness under normal laboratory conditions (room temperature ranging between 20 °C and 30 °C, and relative humidity ranging from 20% to 40%) for about 24 hours [7], [8].

The reflection VHGs are recorded in a two beams holographic optical setup as shown in Fig. 1a. An original longitudinal mode Nd:YVO4 laser ($\lambda = 532$ nm) is used as light source, with a recording intensity of 35 mW/cm^2 at the spatial frequency of 333 l/mm. The spatial frequency could be controlled by changing the angle of the two recording beams. In this work, the angle of the two recording beams is 150°, where the reflection VHG is designed to be input in the angle of 0° and output in the angle of 30° during reconstruction. After exposed to the laser beams, the photopolymer samples are exposed under UV-light ($\lambda = 365$ nm) for 3–5 minutes. Then, the samples are heated at 80–90 °C for 15 minutes. Finally, the Ag thin film is deposited on the VHGs by thermal evaporator in a vacuum chamber at 6.5 $\times$ 10–4 Pa.

A diffraction efficiency measurement system of the reflection VHG was shown in Fig. 1b.The incident beam from the laser (532 nm) is measured by a laser power meter (VLP-2000, China) without VHG on the rotational stage, and P0 is the incident (probe beam) intensity. With a VHG on the rotational stage, a laser power of the first diffraction beam is P1. Furthermore, the incident angle could be changed by adjusting the rotational stage. As a result, the first diffraction efficiency is defined as $\eta = \frac{P_1}{P_0} \times 100\%$.

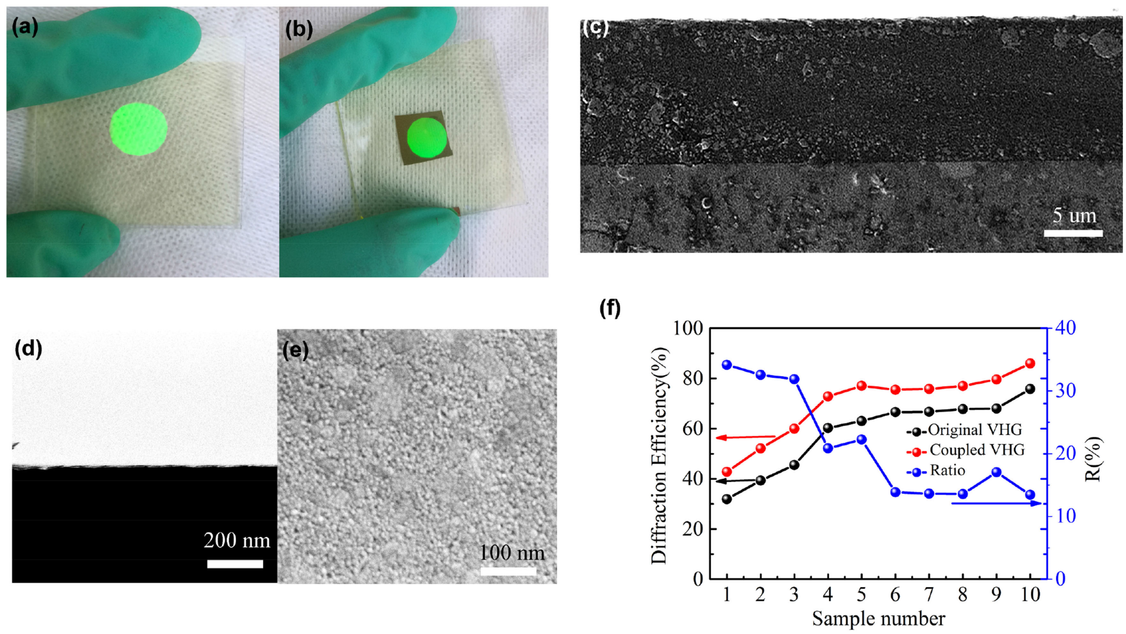

Fig. 2. (a) Optical photo of the original VHG. (b) Optical photo coupled VHG. (c) SEM image of cross-section view and the thickness of the VHG. (d) Amplified cross section image of the VHG. (e) SEM image of the coupled Ag film. (f) Diffraction efficiencies and relative variation ratios of the VHGs.

3. Results

Fig. 2a gives the optical photo of an uncoupled VHG (the green round spot). The central wavelen which indicated higher diffraction efficiency. gth is measured as 532 nm, and beams around 532 nm are diffracted out in the angle of 30°. The Ag thin film coupled VHG is shown in Fig. 2b, comparing with original VHG, a cubic Ag film is coupling with the VHG.

Fig. 2c shows the scanning electron microscope image of the Ag thin film coupled VHG, Fig. 2c is a cross-section view and the thickness of the VHG is measured as 12 μm. Magnified image of the interface between the Ag thin film and VHG is shown in Fig. 2d, where thickness of the Ag thin film is nearly 22 nm. Then top view of the Ag thin film is presented in Fig. 2e. From the nanometer-scale image, the surface of the Ag thin film is in high quality.

In order to investigate the accurate diffraction efficiency enhancement of the Ag coupled VHGs, several samples with different original efficiency are fabricated for comparison. The original efficiency could be controlled by the exposure energy.

The recording density here is chosen from 30 mW/cm^2 to 40 mW/cm^2 for different diffraction efficiency and the best exposure energy is 35 mW/cm^2. The first order diffraction efficiency comparison of before and after coupling the Ag thin film on the VHGs are shown in Fig. 2f. Relative variation ratio of the diffraction efficiency between original VHG and coupled VHG was defined to be R, which could be calculated by $R = \frac{\eta_2 - \eta_1}{\eta_1} \times 100\%$. Diffraction efficiencies of the original VHG samples are ranging from 31.9% to 75.8%, after depositing the Ag thin film on the VHG, the efficiency increased from 42.8% to 86%. Before and after coupling the Ag thin film, the relative variation ratio of the efficiency ranged from 34% to 13%. Interestingly, the enhanced diffraction efficiency is related to the original efficiency. As a result, the Ag film coupled VHGs could also increase the uniformity of the VHGs in large-area waveguide.

To understand the enhancement process of the Ag coupled VHGs, we use numerical simulation to calculate the diffraction efficiency variety. As shown in Fig. 3a, only the first order diffraction beam of the reflection VHG1 is effective in the holographic waveguide display, and the existence of other order diffractions restricts the increase of the first diffraction efficiency. We propose a novel structure

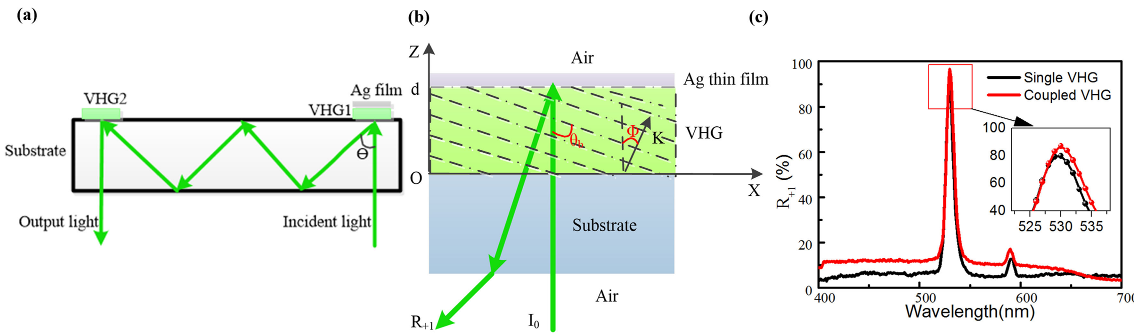

Fig. 3. (a) Schematic of the holographic waveguide display system using the Ag thin film coupled grating. The Ag thin film is evaporated on the upper surface of the in-coupler VHG. (b) Structures of the VHG coupled with the Ag thin film. (c) Simulation results of the first order diffraction efficiency with and without Ag thin film on the VHG.

of the Ag thin film coupled reflection VHGs to enhance the first order diffraction efficiency. To study the redistributed optical field and the first order diffraction efficiency when the VHG is illuminated by light at the Bragg angle, a numerical model is used to analyze the first diffraction efficiency of the coupled VHG.

The structure of the VHG is shown in Fig. 3b, and Rigorous Coupled-Wave Analysis (RCWA) [9] is used to simulate the original and coupled VHG theoretical model.

The relative permittivity in the modulated region ($0 < z < d$) is

$$n(x, z) = n_2 + \Delta n\cos[K(x\sin\Phi + z\sin\Phi)] \tag{2}$$

where n2 is the average refractive index of the photopolymer, Δn is the amplitude of the refractive index modulation, Φ is the grating slant angle, and $K = 2\pi/\Lambda$, which is the grating vector. The refractive index in the unmodulated regions ($z < 0$ and $z > d$) is n1 and n3 respectively. When the light waves illuminate a volume hologram, the Bragg equation should satisfy

$$2n_2\Lambda\sin\theta_b = \lambda \tag{3}$$

Where Λ is the period of the grating, n is the average refractive index of the polymer, θb is the Bragg angle, and λ is the wavelength of the illuminating light in free space. θb is equal with the half angle of the two recording beams when Bragg equation is satisfied in reproduction.

Here the recording wavelength of the laser is 532 nm, the polymer layer is perpendicular to the incident recording wave and its average refractive index $n = 1.48$. Λ could be calculated to be 186 nm by Eq. (3), and $\theta b = 75°$. The thickness of the VHG is $d = 12\,\mu m$, $\Delta n = 0.02$, $\Phi = 15°$, $n1 = 1.5$ (glass) and $n3 = 1$(air). Refractive index in the modulation area could be calculated by Eq. (2).

The RCWA simulation results are shown in Fig. 3c. The central wavelength of the original VHG (the black solid line) is 530 nm, and the first order diffraction efficiency is 85%. After depositing the Ag thin film on the VHG, the first order diffraction efficiency increased to 95% (the red solid line), meanwhile the central wavelength is still 530 nm. It could be assumed that the Ag thin film decreased the forward diffraction, corresponding with an increase of the first order diffraction in the coupled VHG. The improvement of diffraction efficiency here is verified with the experiments results as shown in Fig. 2f.

Although the results from simulation support the diffraction efficiency enhancement in experiments, the simulation is not completed. Some less important factors such as exposure energy and energy loss from substrate and heat are not considered. More convincing evidence would be investigated in our future work.

4. Conclusions

This work proposed a novel structure to enhance the first order diffraction efficiency of VHGs which could be used as the in-coupler in holographic waveguide display system. The Ag thin film coupled in the VHG could increase the reflectivity of the device and decrease the transmission light so as to enhance the efficiency of the first order diffraction beams. Experimental results demonstrated that the first diffraction efficiency of coupled VHG is enhanced which is well consistent with the simulation results. Although we have stated the enhancement of Ag coupled VHGs, we can't dismiss the results are based on one kind commercial photopolymer. For other photopolymers, the coupling methods would be more complicated.

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