Evaluation of Diffraction Orders Efficiency of Laguerre-Gaussian Beam Generated by the Phase and Amplitude Fork Grating Applied on Spatial Light Modulator

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ABSTRACT— **In this paper, Laguerre-Gaussian beams are produced by Computer Generated Hologram (CGH) on Spatial Light Modulator (SLM). The realization of CGH on SLM is simulated by the scalar diffraction theory. At first, Laguerre-Gaussian beam generation process is simulated by diffraction of laser light from phase and amplitude fork gratings in two types: blazed and binary grating and the results are compared. The higher efficiency is obtained for the blazed phase grating in the first order which is more important in our study. Recorded data from the experiment shows a good agreement with simulation results. In order to evaluate the topological charge of the generated Laguerre-Gaussian beam, the Mach-Zehnder interferometer setup is used.**

KEYWORDS: Binary and blazed Grating, Computer generated Hologram, Laguerre-Gaussian beam, Spatial Light Modulator.

I. Introduction

The light beam carrying orbital angular momentum (OAM) is a new type of structured light beams have attracted increasing attention during the past decades due to their important applications. Some of the applications of OAM are: increasing the capacity of free space optical communications and quantum communications [1], optical tweezers [2], in astronomy for halo imaging [3], etc. The most important feature of the optical vortices is their ability to heal themselves in propagation through the turbulent atmosphere [4].

Laguerre-Gauss beams have a helical phase front $\exp(il\varphi)$, where each photon carries orbital angular momentum $\ell\hbar$ and ℓ describes the beam mode. ℓ, φ are called topological charge and azimuthal angle, respectively. $\hbar$ is the Planck's constant divided by 2π [5].

It has always been a challenge to produce these beams due to the inaccessibility of a light source which is capable to tailor them. A practical and feasible idea for recording and producing arbitrary beams is holographic method. In this method, the beam carrying the optical vortex interferes with a plane wave and creates a fork-shaped pattern. The CGH pattern can be generated on the SLM, and by diffraction of light through the fork pattern made by computer one can observe the optical vortices in different diffraction orders. There are amplitude and phase holograms. In amplitude holograms, some part of light is transferred and the other part is absorbed by the opaque regions in the hologram. The amplitude modulated output light is scattered in a way that obtain a certain phase front defined by fringes pattern.

In contrast, in the phase holography, there isn't any obstacle for propagation of light through the hologram and the phase of transmitted beam is changed spatially by optical path difference to the wavefront.

A useful quantity for holography description is its diffraction efficiency which is defined as the ratio of the power at a desired diffraction order (P_m) to the input power (P_0). E_m is the nth order efficiency which is defined as $E_m= P_m/ P_0$. In the amplitude holograms, the half of input power on average is lost due to transmission through opaque fringes, thus they are less efficient compared to the phase holograms. Power management in the diffraction orders has been a challenging issue for increasing potential applications [6].

One of the production methods for optical vortices is printing the fork amplitude hologram pattern on high resolution lithographic films. Photographic films were used to make amplitude gratings and the bleaching process was applied for generating phase holograms [7]. Multi-ring structure of Lagurre-Gaussian beams were produced by using the gratings on photographic films[8].The other method is application of SLM. SLMs are display monitors based on liquid crystals. By changing the fork grating, it is possible to make optical vortices with various topological charges very fast.

SLM operation is based on applying rotation of polarization light vector in each pixel and one can generate an amplitude hologram by using two perpendicular polarizers on each side of it. By rotation of dipoles of a liquid crystal, a phase delay is generated which can be used for producing phase holograms.

Therefore, SLM application is preferred to the printed or etched gratings [7]. Since the shape pattern of grating plays a significant role in the hologram efficiency, there are some studies about the size and pattern type. Sinusoidal and binary type is studied in [6]. In our previous study, a high resolution SLM is considered and its operation under phase and amplitude modulation is investigated [9]. In this paper the efficiencies of diffraction orders of the Laguerre-Gaussian single annular rings generated by SLM are obtained and the detection is made by interferometric methods. Here two different binary and blazed types are considered and the experimental results obtained from them will be compared.

II. Theory and Simulation

In diffraction theory a grating can be formulated as a transfer function.

In amplitude type, the grating function will be the transfer function. The binary amplitude grating is defined by the following equation:

$$g_1(\alpha) = \frac{1}{2}\left(1 + \mathrm{sign}(\cos(\alpha))\right), \qquad (1)$$

where sign function produces two levels of zero and one for binary states.

Transfer function of a binary grating is obtained by convolution of a rectangular function (rect) for creating 0 and 1 binary states in a comb function (comb) for repeating binary states multiplied by an external rectangular envelope (rect) which determine the grating extent.

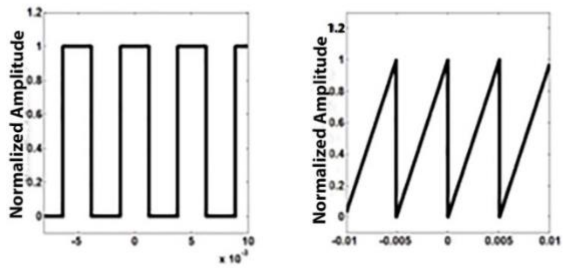
The blazed amplitude grating is defined in Eq. 2, where Mod is used to create the ramp of the blaze function.

$$g_2(\alpha) = \frac{1}{2\pi}\,\mathrm{Mod}(\alpha, 2\pi). \qquad (2)$$

A blazed grating is made by convolution of three following functions: a ramp function (ramp) for showing the phase difference in one period of blazed grating, a comb function (comb) for repeating the ramp function and a rectangular envelope (rect.) which determines the extent of grating.

The amplitude grating of blazed and binary profiles are shown in Fig. 1. A fork pattern is obtained by interfering a reference plane wave with a vortex beam wave which finally becomes the binary grating fork pattern [10].

The binary and blazed amplitude hologram gratings of the above functions are illustrated in Fig. 2 for topological charge =1.



(a) (b)

Fig. 1. Transverse grating sections. (a) the binary profile and (b) the blazed profile.

Fig. 2. Fork grating for generation of vortex beam with topological charge l=1. Right: the binary hologram, Left: the blazed hologram.

For the phase holograms, the Eq. 3 gives the transfer functions of the hologram gratings.

$$t(x_1, y_1) = e^{iag}, \tag{3}$$

where g denotes the type of grating and a is the modulation depth of the hologram grating.

A Gaussian beam, $\Psi(x, y)$, is transferred through above gratings and its far field pattern is obtained by Fourier transformation of the transfer function, t(x,y), multiplied by Gaussian input beam:

$$F\{\Psi(x,y)t(x,y)\} = \iint_{-\infty}^{+\infty} dxdy\Psi(x,y)\, t(x,y) \exp[-i2\pi(x\xi + y\eta)]. \tag{4}$$

Diffracted far field patterns for binary phase, binary amplitude, blazed phase and blazed amplitude grating is depicted in Fig. 3. It can be seen that odd orders existed in binary phase grating, zeroth order is added in the binary amplitude grating. All orders are seen in blazed amplitude grating while only the first order is appeared in blazed phase grating.

Since SLM is a typical digital optical element, for simulating its diffraction of light waves, the specific SLM parameters such as actual size, pixel dimension, maximum phase variation should be considered. Consequently, the sampling effect of the 2-dimensional pixel array of SLM causes periodically distributed diffraction field in space. We can adopt the design of blazed grating so that its diffraction is mainly concentrated on a specific diffraction period and order.

Equation 5 defines efficiency of mth order of diffraction that N is the number of steps that the phase changes from its highest value to its lowest value in a fringe on SLM [10,11].

$$\eta = \left[\frac{\sin\left(\frac{m\pi}{N}\right)}{m\pi} \frac{\sin[\pi(m-1)]}{\sin[\pi(m-1)/N]}\right]^2. \tag{5}$$

It can be easily found using Eq. 5 that if N=25, the diffraction efficiency of + 1 order increases to 99.5≈ 100%.

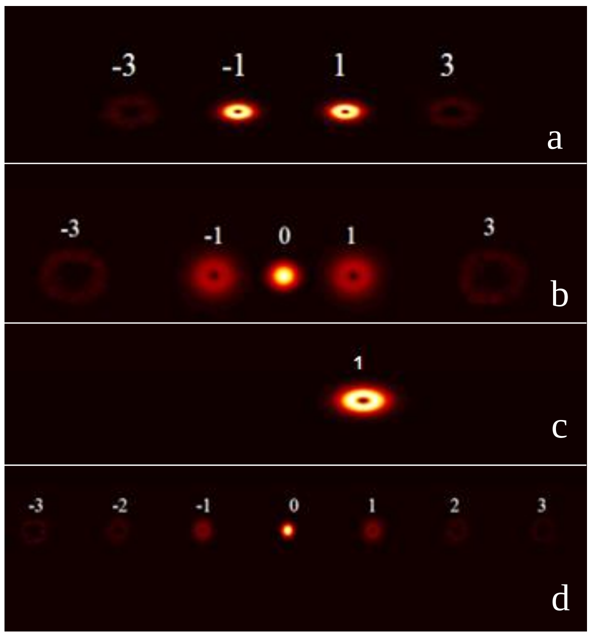


Fig. 3. Diffraction orders from: a) binary phase hologram b) binary amplitude hologram c) blazed phase hologram d) blazed amplitude hologram.

It can be seen that the more steps, the higher the diffraction efficiency of +1 order, the more concentrated light energy, and the closer the profile of the binary step structure to the blazed grating with zigzag profile [11].

III. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 4. Laser light illuminates the CGH pattern on the SLM and efficiency of each diffraction order of the gratings which is separated by a moving pupil is measured by a PIN diode photodetector. As shown in the experimental diffraction pattern from amplitude hologram grating in Fig. 5, all orders of diffraction appear in the blazed type, while zero order and odd orders observed in the binary grating. As a result, power density in odd diffraction orders of binary type is expected to be higher than the blazed grating where energy is distributed in all diffraction orders which is in agreement with the simulation results.

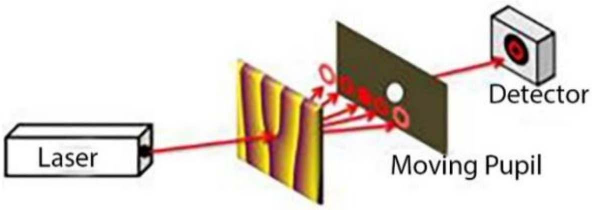


Fig. 4. Efficiency measurement of the diffraction order setup.

In order to justify the performance of gratings Laguerre-Gauss beams are interfered with plane wave to produce the fork pattern.

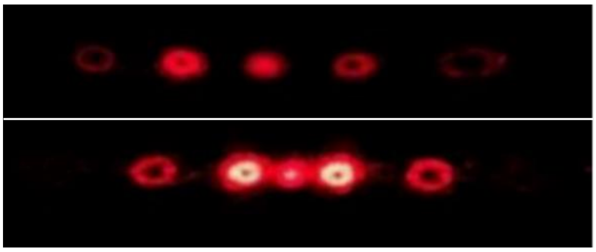


Fig. 5. Diffraction results from the amplitude hologram: upper is from the blazed grating and lower is from the binary grating.

The topological charge of Laguerre-Gauss beam is the same with what is obtained from the fork grating interferometry. Mach-Zehnder interferometric experimental setup is shown in Fig. 6. Laguerre-Gaussian beam generation process is simulated by diffraction of laser light from phase and amplitude fork gratings in two types. In Table 1, the theoretical simulation and experimental results for phase and amplitude holograms of the two gratings are described.

Fig. 6 Mach-Zehnder interferometer setup, the fork grating is obtained from Mach-Zehnder which shows the topological charge one (l=1).

Table 1. Efficiencies of different gratings

Hologram efficiency	**Amplitude**		**phase**
Grating Type	**Experimental**	**Simulation**	**Simulation**
Blazed	3%	3.5%	100%
Binary	9%	10%	4%

IV. CONCLUSION

In this paper, Laguerre-Gaussian beams are produced by CGH technique on SLM. Result shows the efficiencies of the amplitude hologram for the binary and blazed gratings are lower than the phase holograms. If one wants to concentrate the total energy in a desired diffraction order, the blazed phase hologram can be used to generate 100% efficiency. Since the applied SLM in this experiment couldn’t produce the required phase difference, it is better to be used as an amplitude hologram. In experiment 9% efficiency is obtained for the binary grating while the blazed grating has 3% efficiency. Thus, the blazed amplitude holograms have lower efficiencies with respect to the binary holograms, because of the existence of all diffraction orders in them. Because of absorption, the experimental results are slightly lower than the stimulated ones. It must be noticed that energy distribution response in different diffraction orders is dependent on the choice of transfer function for grating. Therefore, in order to increase the efficiency, one can obtain the best required transfer function by reverse optimization method.

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