Geometric-Phase Polarization Fan-out Grating Fabricated with Deep-UV Interference Lithography

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Abstract We report the design, fabrication and testing of a highly efficient polarization fan-out grating for coherent beam combining working at 1550 nm. The grating design exploits the geometric-phase effect. Deep-UV interference lithography is used to fabricate the designed grating. Such a polarization fan-out grating demonstrates several advantages that are ideal for laser beam combining.

1. Introduction

Coherent beam combining offers a path to higher radiance of laser sources by combining the power produced from a number of lower-power gain elements. Dammann gratings are commonly utilized as a fan-out element for beam combining because their binary phase feature facilitates the design and fabrication. However, the power diffracted to undesired higher orders plagues the splitting efficiency and deteriorates the overall efficiency of the laser combining system. Multilevel and continuous phase gratings can considerably increase the fan-out efficiency at the expense of fabrication with high complexity and cost.

Recently optical elements taking advantage of the geometric-phase shift have attracted interest and spur numerous applications. Contrary to adjusting the optical path length, the geometric-phase shift arises from the evolution of a lightwave through an anisotropic parameter space [1]. The geometric-phase holograms (GPHs) can be made extremely thin with an arbitrary and continuous phase profile. Two leading approaches have been adopted to fabricate GPHs including metasurfaces consisting of carefully aligned V- or rod-shaped nanoparticles and liquid crystals assisted by the photo-alignment technique. However, transmissive metasurfaces are generally low in efficiency and photo-alignment liquid crystals are not highly resistant to laser induced damage. Therefore fan-out gratings made with these two techniques are not

quite suitable for high-power laser beam combining purposes. To surmount this hurdle, we fabricate the geometric-phase fan-out grating on silicon with deep-UV interference lithography. Although the interference lithography is limited in its use due to the inability to create arbitrary geometries, it is sufficient to fabricate geometric-phase fan-out gratings that consist of blocks of binary subwavelength structures with various orientations. The intrinsic nature of the interference lithography also makes the fabrication of large-area gratings an inexpensive task.

2. Grating design and fabrication

2.1. Geometric-phase fan-out grating

The geometric phase was first described by S. Pancharatnam in 1956, and applied to quantum mechanics by M. Berry in 1984 [2-3]. The geometric-phase shift can be generated by inhomogeneous and anisotropic optical elements and imparted on two of the three outgoing waves: the primary wave and the conjugate wave [1]. By controlling the polarization state of the incident wave and the form birefringence of the material, it is possible to direct all the power to the primary wave or the conjugate wave. The schematic of a 16-phase-level 1-by-5 beam splitter is shown in Fig. 1. The grating consists of 16 periods and each period is constituted by eight segments. Each segment is formed by binary subwavelength structures with different widths (40.8 μm, 44.1 μm, 34.2 μm, 30.9 μm) and orientations (123.75º, 33.75º, 22.5º, 0º)

as listed in Fig. 1. Therefore the geometric-phase shifts provided by each segment are 1.375π, 0.375 π, 0.25 π and 0 respectively. The etching depth of the binary structures, according to the rigorous coupled wave analysis, is 666 nm for the pitch of 314 nm to maximize the power distributed to the primary wave.
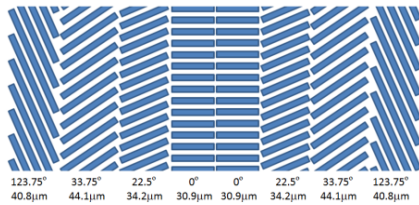

Fig. 1. Schematic diagram of the 1-by-5 geometric-phase fan-out grating (one period).

2.2. Deep-UV interference lithography

The deep-UV interference lithography system consists of a diode-pumped continuous-wave YAG laser that is quadrupled to 266nm. The laser beam is expanded, collimated and shaped to produce a uniform illumination to cover a 4-inch diameter at the Lloyd's mirror stage as shown in Fig. 2 [4]. Since the mirror and sample are both physically mounted on the Lloyd's mirror stage, the effect of vibration between the two beams is reduced considerably, allowing for a sharp pattern even after very long exposure times.
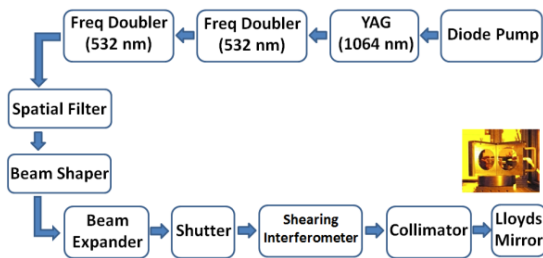

Fig. 2. The optical system of the deep-UV interference lithography.

The period of the fringes created by the two beam interference is given by:

$$\Lambda = \frac{\lambda}{2\sin\theta} \quad , \qquad (1)$$

where λ is the wavelength (266 nm) and θ is the incident angle. The incident angle is controlled by the rotation of the stage and a 25-degree incident angle renders a period of 314 nm. The size of the grating is 4.8 mm by 4.8 mm. The grating contains four orientations of subwavelength

structures and each orientation is accomplished with one exposure. A grating of a larger size can be fabricated just by expanding the laser beam. The scanning electron microscopy (SEM) images of the grating are presented in Fig. 3 showing great fabrication quality. The gaps between adjacent segments have negligible effects on the far-field intensity distribution.
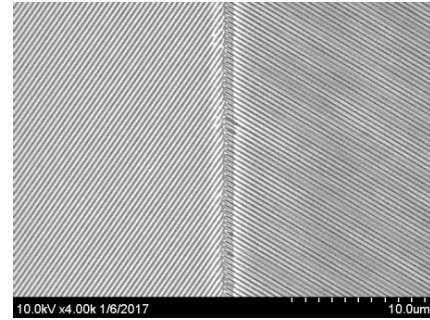

Fig. 3. SEM images of the geometric-phase fan-out grating.

3. Grating test

The grating is tested with a left-handed circular polarization (LHCP) laser beam at 1550nm. The far-field intensity distribution is measured by an infrared camera. The experimental setup is illustrated in Fig. 4.
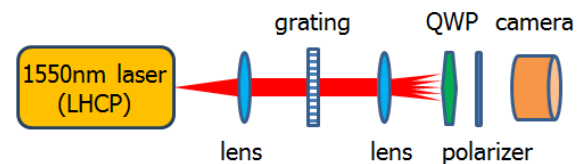

Fig. 4. Schematic of grating test setup. QWP: quarter-wave plate.

The transmitted field of the grating splits into five individual beams and their polarization states are all right-handed circularly polarized (RHCP) verified by a quarter-wave plate (QWP) and a linear polarizer. The far-field intensity distribution is shown in Fig. 5.
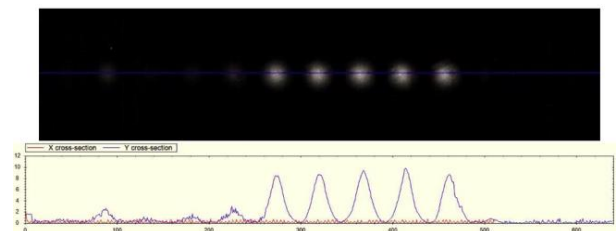

Fig. 5. The far-field intensity distribution captured by the

camera.

The five desired orders are theoretically to have identical power and the experimental result gives a power ratio of $\eta_{-2}:\eta_{-1}:\eta_0:\eta_1:\eta_2 =1 : 1.01 : 1.1 : 1.15 : 1.01$.

Conclusions

We design and fabricate a geometric-phase polarization fan-out grating with deep-UV interference lithography. The grating splits one LHCP laser beam into five RHCP laser beams of almost identical power. The grating may find application to coherent beam combining by coupled laser resonators.

Acknowledgment

Reference

[1] M. J. Escuti, J. Kim and M. W. Kudenov, "Controlling Light with Geometric-Phase Holograms," Opt. and Photon. News, 27(2), 22-29 (2016).

[2] S. Pancharatnam, "Generalized theory of interference, and its applications. Part i. Coherent pencils," Proc. Indian Acad. Sci. A 44, 247–262 (1956).

[3] M. Berry, "Quantal phase factors accompanying adiabatic changes," Proc. R. Soc. London Ser. A 392, 45–57 (1984).

[4] D. Lombardo, P. Shah, P. Guo, and A. Sarangan, "Deep-UV interference lithography combined with masked contact lithography for pixel wiregrid patterns," In SPIE Advanced Lithography, International Society for Optics and Photonics (2016).