Low divergent diffractive optical element for remote detection

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The low divergent Dammann grating is researched for the potential applications in aerospace. A laser-beam writing system is developed for writing the low divergent Dammann grating. The uniformity and efficiency of the Dammann grating are presented in this letter. The novelty of this letter is to demonstrate a low-cost and effective method to fabricate low divergent Dammann grating.

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Micro-optical elements have been widely used in various areas such as binary optics, spectroscopy, optical interconnects, integrated optics, quantum electronics, and acousto-optics. As the key component in the field, grating, especially, has attracted much attention from researchers due to its wide applications, such as astronomical detection, military application, industrial and scientific research[1]. In particular, binary surface-relief gratings for array illumination in the Fourier-transforming plane, or, the so called Dammann grating[2], is the basic component of many optical systems. Because of the long distance of light path and the limited small-angle area of the sensor, it is significant to have a research on low divergent Dammann gratings[3].

In order to fabricate the low divergent Dammann grating, we develope a laser direct-writing system and find out the suitable method[4]. It is known that the fabrication of the grating has developed rapidly; various fabricating methods have been reported in the past decade[5]. The holographic-interference method is limited by the size of the lens, more seriously, this method can hardly fabricate Dammann grating. The electron-beam writing can fabricate high-quality masks; however, the masks writing by electron-beam is expensive for the large-sized mask, which leads to high production costs and delay time. Recently, laser direct-writing technique has received extensive attention; this technique has been demonstrated for microfabrication and nanoscale patterning applications[6]. Laser direct-writing is a mask-less lithography with using a high-precision laser beam that scans on the sample coated with the photoresist, photosensitive material, and other heat-sensitive materials[7]. As we know, Dammann gratings are pure phase gratings which can generate arrays of uniform-intensity beams from an incoming laser beam of monochromatic light[8]. In these cases, laser direct-writing techniques for the fabrication of Dammann grating have considerable advantage, such as cost effectiveness, flexibility in terms of irregular sub periods.

In this letter, we report on fabrication of a 1×8 Dammann grating for the wavelength of 1064 nm. The laser with a wavelength of 1064 nm is used in laser ranging, laser-guided, coherent communication, atmospheric research, and so on; the Dammann grating for the light with a wavelength of 1064 nm is fabricated.

The modulated binary phase grating was proposed by Dammann and Görtler in 1971, this grating can produce multiple images of an object with high efficiency, which was later named Dammann grating. According to the Dammann grating transitional-points study reported by Zhou *et al.*[9], the 1×8 Dammann grating transitional-points are $x_1 = 0.06185$, $x_2 = 0.17654$, $x_3 = 0.20858$, $x_4 = 0.31797$. We make the divergence angle $\theta = 1.2$ mrad, wavelength λ=1064 nm. According to the grating equation, the grating period

$$d = \frac{\lambda}{\sin\theta} = 886.67\,\mu\text{m}. \qquad (1)$$

According to the research by Morrison[10], the transitional-point of this Dammann grating is $X_1 = 54.84\,\mu$m, $X_2 = 156.32\,\mu$m, $X_3 = 184.94\,\mu$m, $X_4 = 281.93\,\mu$m, $X_5 = 443.33\,\mu$m, $X_6 = 498.17\,\mu$m, $X_7 = 599.87\,\mu$m, $X_8 = 628.28\,\mu$m, $X_9 = 725.27\,\mu$m. The target of the fabrication is to make high efficient and excellent uniformity gratings. Dammann grating is binary phase distribution, which leads to a simple process for fabrication using the laser writing facility[11].

Our laser direct-writing system has three parts: the direct writing lithography optical system, the auto-focus system, and the mechanical and electronic control module. Our setup is shown schematically in Fig. 1.

In the laser direct-writing lithography optical system, a 405-nm fiber coupled laser diode system is used as the light source to expose the photoresist. The laser module delivers exceptional power stability with low amplitude noise. Pinhole and 4f lens group are filters for the 405-nm laser beam. A microscope objective with numerical aperture NA = 0.90 is used. The entrance pupil of the microscope objective is illuminated by a parallel beam. Diameter d of the focus are given by $d = k\lambda/\text{NA}$. The value of k depends on the illumination of the microscope objective.

To write the designed pattern, an auto-focus system is necessary. Generally speaking, the movement of the autofocus has high frequency and low amplitude to

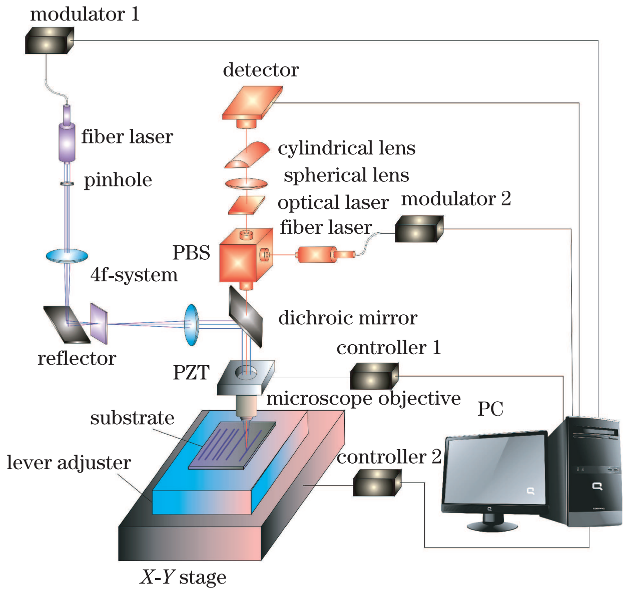


Fig. 1. Laser direct-writing system.

compensate the positional deviation of mechanical vibration and the tilted sample. We need PZT to accomplish the accurate and high frequency movement. A 650-nm laser is used for its insensitivity to the photoresist. The laser beam is reflected by a polarization splitting prism, and then becomes a linear polarized light from a circularly polarized light through a quarter-wave plate. The laser beam passes through the dichroic mirror and the microscope objective, then reach the photoresist. After reflection from the photoresist, the laser beam propagates through the polarization splitting prism. Because of the changed polarization state, the laser beam can pass through the polarization splitting prism, optical filter, a lens, a cylindrical lens, then it finally reaches the quadrant detectors. The quadrant detectors will get the focus error signal (FES) and make it become electrical signal. This signal will be feedback to control the movement of the PZT by a computer, which leads to the movement of the microscope objective for autofocus control.

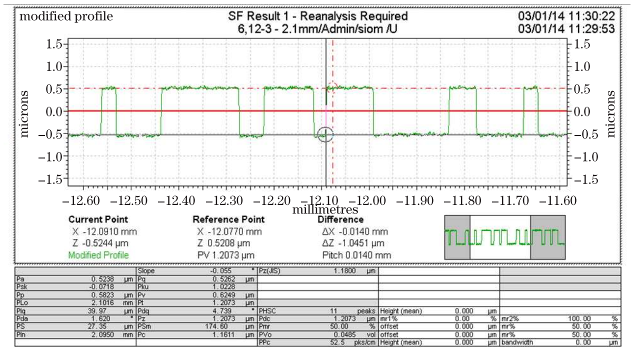
A nano-precision linear stage is the major part of the mechanical and electronic control module. The new hybrid system overcomes the limitations of conventional precision positioning systems by combining the well-known advantages of piezo-flexure-drives (nanometer resolution and very rapid response) with the long travel ranges and high holding forces of a servo-motor. The stage allows velocities to 125 mm/s with an encoder resolution of 2 nm. On the mechanical side, long travel ranges with nanometer precision is accomplished by decoupling the positioner's motor-balls crew-drive by frictionless flexures and stiff, highly responsive PZT.

In order to obtain the required exposure pattern, we have to control the velocities of the stage and the defocusing amount. What's more, the modulation of the intensity is necessary. The velocity of the x-motion is 1 mm/s, the x-motion controls the period of the grating, so the displacement accuracy of the stage is the most sensitive parameters, we can use an air-floating platform to reduce the vibration as well as improve the precision of the stage. The velocity of the y-stage is 10 mm/s, the y-motion undertakes the grating strips, the straightness accuracy is the most important parameters for y-motion. We modulate the defocusing amount and intensity of the laser beam to achieve the various duty cycles. After these preparations, we need an experimental environment without external stray light and violent vibration.

In order to eliminate the intensity of the zero-order, the Dammann grating need to be precisely etched with etching depth of 1040 nm. Wet-chemical-etching with HF is an important part of our experiment. The etching temperature was controlled at 20 °C; the etching time should also be controlled precisely. Under these circumstances, we can achieve the desired depth. Figure 2 shows the surface profile of the etched Dammann grating measured by the Taylor Hobson profiler, from which we can see the etching depth of 1045 nm that is close to the theoretical one of 1040 nm. Figure 3 shows the fabricated Dammann grating.

Then we use a 1064-nm laser to test the Dammann grating, Table 1 shows the measured roughly-equal intensities at different orders of the fabricated Dammann grating.

So the efficiency of this Dammann grating is μ=57.16%, the theoretical efficiency is 76.15%. There are many causes of error between experimental and theoretical values, for example, although our linear motion stage has high precision, machining error(pitch and yaw of the linear stage) still exists during our work; the wet-chemical-etching should not be reused if a high-quality surface



Current Point
X -12.0910 mm
Z -0.5244 µm
Modified Profile

Reference Point
X -12.0770 mm
Z 0.5208 µm
PV 1.2073 µm

Difference
ΔX -0.0140 mm
ΔZ -1.0451 µm
Pitch 0.0140 mm

			Slope	-0.055	°	Pz(JIS)	1.1800	µm						
Pa	0.5238	µm	Pq	0.5262	µm									
Psk	-0.0718		Pku	1.0228										
Pp	0.5823	µm	Pv	0.6249	µm									
PLo	2.1016	mm	Pt	1.2073	µm									
Plq	39.97	µm	Pdq	4.739	°	PHSC	11	peaks	Height (mean)	0.000	µm			
Pda	1.620	°	Pz	1.2073	µm	Pdc	1.2073	µm	mr1%	0.00	%	mr2%	100.00	%
PS	27.35	µm	PSm	174.60	µm	Pmr	50.00	%	offset	0.000	µm	mr%	50.00	%
Pln	2.0950	mm	Pc	1.1611	µm	PVo	0.0485	vol	offset	0.000	µm	mr%	50.00	%
						PPc	52.5	pks/cm	Height (mean)	0.000	µm	bandwidth	0.00	µm

Fig. 2. Surface profile of the fabricated Dammann grating.

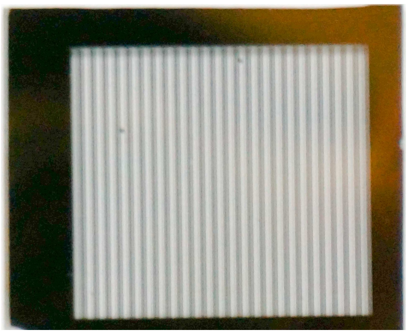


Fig. 3. Low divergent Dammann grating.

Table 1. Measured Roughly-equal Intensities at Different Orders of the Fabricated Dammann Grating

Order	−4	−3	−2	−1	1	2	3	4	Total
Intensity (μW)	95.2	103.4	104.9	98.8	97.7	98.9	99.0	102.4	1400

profile is required, the etching process is limited by the defects of the masking layer and the penetration of the etchant through these defects, a fast etch rate of glass will lead to a deeper etching while the defect will maintain at the same rate each time[12].

The uniformity of the Dammann grating is

$$\text{uni} = \frac{\max(I_n) - \min(I_n)}{\max(I_n) + \min(I_n)} = 4.88\%. \qquad (2)$$

According to the experimental data above, this Dammann grating meets our expectations. Laser-direct writing system has the advantage of fabricating variable period gratings. We achieved in controlling the transitional-points and the duty cycle by the accurate displacement and the modulation of the laser beam. For the specific applications, the diameter of the 1064-nm laser beam is smaller than 20 mm, so the size of the fabricated Dammann grating is 20×20 (mm).

In conclusion, we design a 1×8 low divergent Dammann grating with the wavelength of 1064 nm. It is significant to have a research on low divergent Dammann grating; besides, it is necessary to present a low-cost and effective method to fabricate the low divergent Dammann gratings, and then we developed the laser-direct writing system. With this system, a 20×20 (mm) 1×8 Dammann grating for the wavelength of 1064 nm is fabricated. In order to achieve various duty cycles, we can modulate the defocusing amount and intensity of the laser beam. We believe that finding out an appropriate method for the low divergent Dammann grating fabrication has great significant. With this system, we fabricate a large area high-density Dammann grating. Because of the long distance of the light path, the low divergent Dammann gratings are useful optical components in aerospace; the research on low divergent Dammann grating is interesting for practical applications.

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