doi:10.3788/gzxb20154404.0405001

用于光学位移传感器的新型数字编码光栅尺的制作

王宇,陈火耀,刘正坤,郑衍畅,洪义麟,付绍军
(中国科学技术大学 国家同步辐射实验室,合肥 230029)

摘 要:介绍了数字编码光栅尺的结构设计并提出一种制作方法.采用紫外对准光刻、全息光刻及湿法腐蚀结合在(100)硅片上制作母光栅尺,并以具有紫外固化特性的聚氨酯丙烯酸酯为材料,将母光栅尺复制到硬基底上.实验表明,该工艺可重复性高,复制光栅尺的衍射效率高于母光栅尺的90%,并能承受航空环境−55℃~70℃的高低温冲击.光栅尺的制作准确度满足传感器的要求,信号响应准确率100%.该方法可对具有准确度高、图形复杂、工作环境恶劣等特点的微纳米结构的制作提供借鉴.

关键词:光学位移传感器;编码光栅;复制技术;紫外光刻;全息光刻;光传操纵系统
中图分类号:O436;TH162 **文献标识码**:A **文章编号**:1004-4213(2015)04-0405001-5

Fabrication Process of a Novel Digital Encoding Grating Ruler for Optical Displacement Sensors

WANG Yu, CHEN Huo-yao, LIU Zheng-kun, ZHENG Yan-chang, HONG Yi-lin, FU Shao-jun
(*National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei* 230029, *China*)

Abstract: The structure and fabrication process of a novel Digital Encoding Grating Ruler (DEGR) were introduced. In this process, the pattern of DEGR is firstly fabricated on a (100) silicon wafer by combining UV lithography and holography lithography with wet etch technique, and then replicated to a hard substrate using polyurethane acrylate which is UV curable. Experimental results show that the process is highly repeatable. The replicated gratings work properly in the ambient temperature ranging from −55℃ to 70℃, and its diffraction efficiency is higher than 90% of the master one. The fabrication precision meets the requirements of the optical sensor, and the signal response accuracy is 100%. Moreover, this process could be used to fabricate other micro-nanometer structures with high precision, complex pattern and poor working environment.

Key words: Opticaldisplacement sensor; Encoding grating; Replication technique; UV lithography; Holographic lithography; Aircraft control systems
OCIS Codes: 050.2770; 060.2370; 090.2880; 220.4241

0 Introduction

Due to its immunity to electromagnetic interference, optical displacement sensors have become essential component in the aircraft control system. In recent years, the optical sensors based on wavelength encoding are developing fast[1-5]. Among those sensors, digital wavelength encoding optical absolute displacement sensor, which is not only immune to electromagnetic interference but also temperature-insensitive, is quite promising. And the core element of the sensor is a Digital Encoding Grating Ruler

Foundation item: The Technology Innovation Fund for Aviation Industry Corporation of China (No. 2009D61864), the National Science Foundation for Young Scientists of China (No. 11105145)

First author: WANG Yu (1990−), female, Ph.D. degree candidate, mainly focuses on optical displacement sensors. Email: qianyehu@mail.ustc.edu.cn

Supervisor: FU Shao-jun (1952−), male, professor, mainly focuses on diffraction optics and super micro−machining technologies. Email: sjfu@ustc.edu.cn

Contact author: LIU Zheng-kun (1981−), male, Ph.D. degree, mainly focuses on optical sensors and diffractive optical elements. Email: zhkliu@ustc.edu.cn

Received: Sep.30, 2014; **Accepted**: Dec.25, 2014

(DEGR), which is practically a substrate on which several blazed grating units with different line densities are parallel arranged in certain orders. As the line densities of gratings range from several hundreds to more than one thousand, the smallest structure size of the DEGR is less than 1 μm. The structure of the DEGR is so complex and high-precision that many manufacturing methods, such as laser direct writing and machine-ruling, which are used in the manufacturing of traditional code disks[6] doesn't suit any more.

This paper introduces a novel fabrication process of the DEGR. In this process, the pattern of DEGR is firstly fabricated on a (100) silicon wafer by combining UV lithography and holography lithography with wet etch technique, and then replicated to a hard substrate using Polyurethane Acrylate (PUA), which is UV curable. Experimental results show this process is highly repeatable. The experimental performance of the digital wavelength encoding optical displacement sensor is also presented.

1 Sensor principle

1.1 Design of the sensor

The basic system structure of the displacement sensor is illustrated in Fig. 1. Analysis of the operation of the digital wavelength encoding optical absolute displacement sensor begins with a consideration of the basic grating equation, i. e.

$$kn\lambda = \sin\theta_i + \sin\theta_o \qquad (1)$$

Where n is the line density of grating, k is the diffraction order, λ is the wavelength, θ_i is the input angle of the incident light and θ_o is the output angle of the diffracted light. By fixing the locations of optical fibers and collimation system, the angles θ_i and θ_o will be constant. The relationship between the line density and the wavelength are reciprocal.

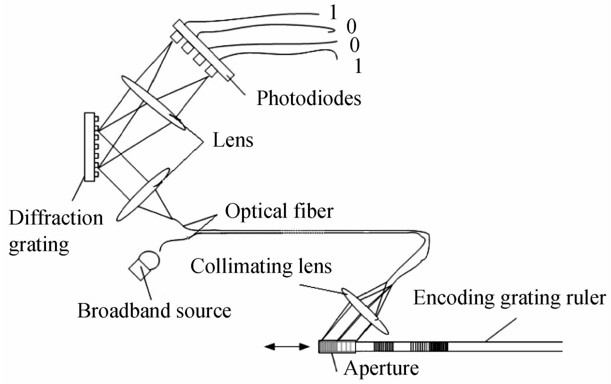

Fig. 1 The diagram of digital wavelength encoding optical absolute displacement sensor

As shown in Fig. 1, a broadband source passes through an specific size aperture and irradiates the surface of DEGR. The aperture is designed to limit the irradiatedarea, which is quite important to the precise response of the sensor. From the Eq. (1), wavelength information carried by the DEGR are converted into digital code by a demodulating system which contains grating and collimating lens. In this sensor, the transmission of information is entirely optical signal. As the line densities of adjacent units are far different, the sensor is insensitive to changes in temperature in theory. This character solves the problem fundamentally exists in varied line-space grating displacement sensor[7-8], which is quite popular in recent three decades. Thus, the optical sensor based on DEGR has a prosperous application in aerospace industry.

1.2 Structure of the DEGR

The range and resolution of the optical displacement sensor literally depend on the design of the DEGR. Fig. 2 shows the typical structure of the DEGR, which is different from traditional micro-nanometer structures. There are several colors and each one represents one kind of grating. The DEGR consists of several units, each unit has a certain length, which is generally 50～300 μm for the requirements of the sensor design. Each unit contains a kind of diffraction grating with identical line spacing. There are generally 4～8 kinds of identical line spacing gratings which are determined by the resolution and length of the sensor on the whole DEGR. R_1, R_2 and R_3 represent 3 parallel rulers with different wavelength codes, and there is a certain misalignment between adjacent rulers. This multi-structure is helpful to obtain higher resolution and range. By optimizing the coding algorithm, a DEGR with 3 parallel rulers and 6 kinds of gratings can achieve more than 100,000 kinds of codes, which is sufficient for the performance requirements of the optical sensor. An example is given in Fig. 3 to further illustrate the principle of DEGR.

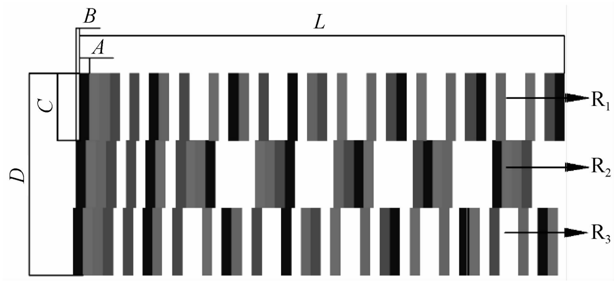

Fig. 2 The typical structure of the DEGR
(L is range, B is resolution, A is unit size, C and D are the width)

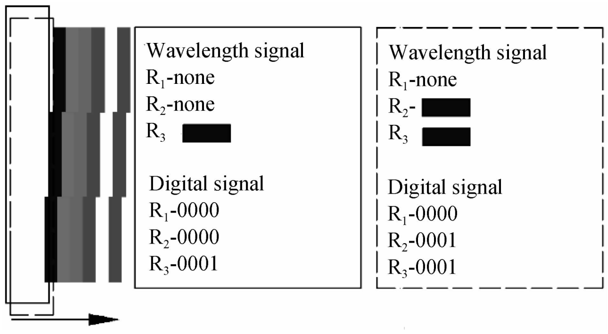

Fig. 3 The signal conversion of the sensor

2 Fabrication process of the DEGR

As the core element of the optical sensor, the DEGR determines the sensor performance greatly. The fabrication process of the DEGR, which combines UV lithography, holographic lithography, wet etching and grating replication techniques, is introduced detailed in this section.

A photo-mask used for UV lithography to emerge the " windows" of grating units was made first. As shown in Fig. 4, windows with the same grating were fabricated in one line, which could be lithography in one process. Gratings with the line density of 40 lines/mm beside the windows were used to align different units between processes, which is of great importance to the fabrication accuracy of the DEGR.

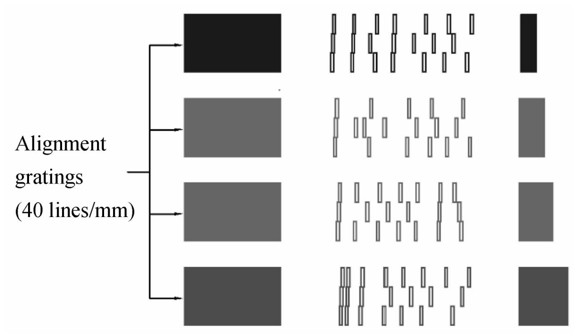

Fig. 4 Thephoto-mask used for UV lithography

1)Substrate preparation. (100) silicon wafer was cleaned in piranha solution (H_2SO_4(%):H_2O_2(%)= 3:1, 90℃) for 30 min, then rinsed in hot DI water and blown dry with N_2 gas. Finally the silicon wafer was baked on a hot plate (120℃) for 2 min. After the cleaning process, layers of silicon dioxide film (100 nm) and chromium film (80 nm) were coated in turns for the next steps.

2) UV lithography. In order to improve the adhesion of the Photoresist(PR), the silicon wafer was ashed for 10 min, then spin-coated with an AZ3100 positive PR and baked 90℃ for 30 min. In Fig. 4, there are 4 kinds of windows, one of which was fabricated by UV lithography firstly, and the others were made until the next cycles (shown in Fig. 5). The PR pattern was formed after developed in NaOH solution (0.5wt. %), and is further transferred to the underlay chromium layer by stripped the exposed chromium film.

3) Interference lithography. The grating corresponds the window previously made was fabricated by interference lithography. The process was similar to the UV lithography. After the grating pattern was formed in the PR, an ICP process was used to etch the silicon dioxide film.

4)KOH etch. Anisotropic wet etch, which is the final main step of the process, was carried out after transferring the grating pattern into the layer of silicon dioxide film. Residual PR was removed before the etching to avoid possible pollution of the etching solution. The blazed grating was formed by immersing the silicon wafer into KOH solution (50wt. %, 40℃). Appropriate etching duration was necessary to achieve desired groove profile.

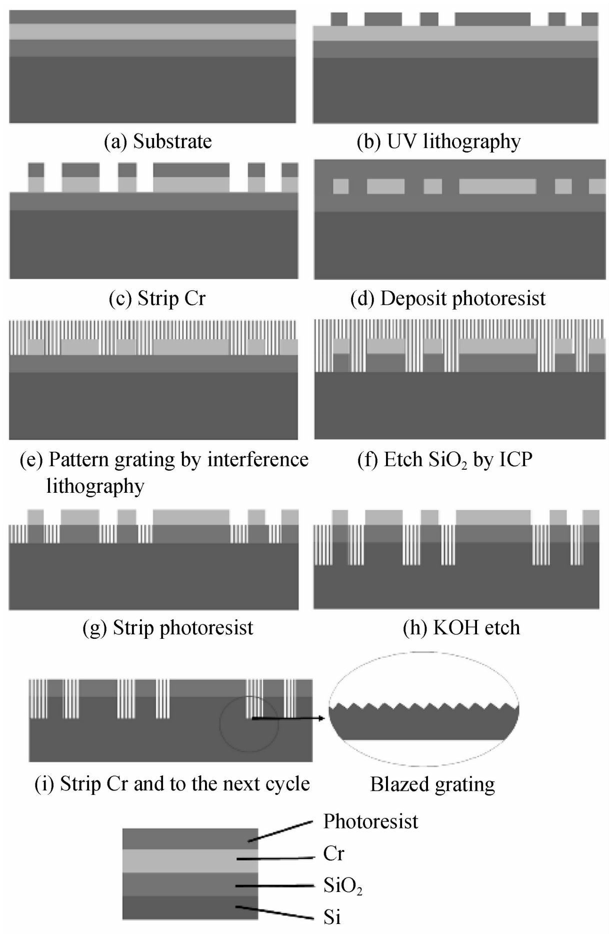

Fig. 5 The fabrication process of DEGR

5) Preparationfor the next cycles and grating replication. The fabrication of one kind of window with blazed grating was completed after stripping the residual chromium film. Other gratings were successively fabricated by repeating the above process. The grating replication technique was carried out to improve fabrication efficiency. The pattern in the

silicon wafer was replicated to a hard substrate using PUA, which is UV curable (shown in Fig. 6).

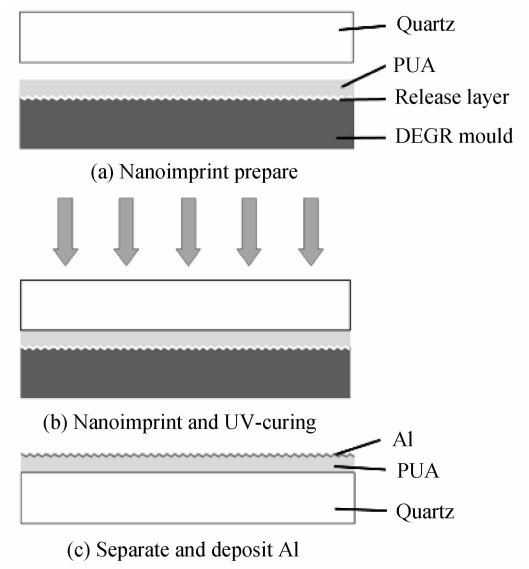

Fig. 6 The process of grating replication

3 Results

Using the process shown in Fig. 5, one master DEGR contains 4 kinds of grating units with line densities of 800～1 300 lines/mm has been successfully fabricated (shown in Fig. 7). And Fig. 8 is the Atomic Force Microscopy (AFM) image of one kind of grating. Then several DEGRs were replicated. A He-Ne laser was used to measure the diffraction efficiency of the gratings, and the results show that the diffraction efficiency of the replicated gratings is higher than 90% of the master one. The environment testing of the replicated gratings was conducted, which found the gratings work properly in the ambient temperature ranging from －55℃ to 70℃.

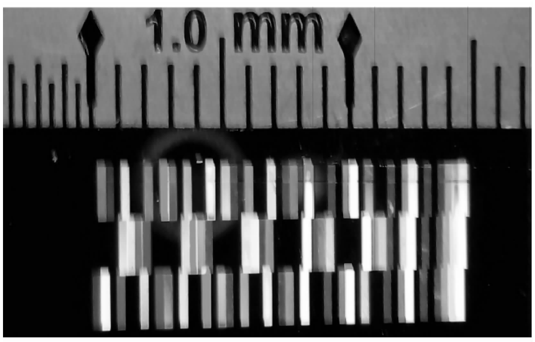

Fig. 7 The photo of one kind of DEGR. This DEGR carriers 150 displacement information

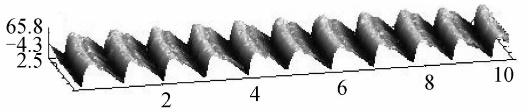

Fig. 8 The AFM image of one kind of blazed grating

The optical displacement sensor for aircraft control system is requested to be highly reliable to adapt to the harsh environment. The sensor range is 50～200 mm, and the linearity has three levels, 0.1%, 0.2% and 0.5%. As the core element of the sensor, the fabrication precision of the DEGR determines the sensor precision and uniformity. As previously mentioned, the DEGR consists of several blazed grating units which are parallel arranged in certain orders. The relative positions of adjacent units and the process stability are the main fabrication error sources.

The relative positon error is mainly caused by the tilt error, which would result in tens of micros position misalignment. For the purpose of evaluation, a DEGR with length of 100 mm was fabricated. In UV lithography process, a couple of gratings with 40 lines/mm were used for alignment. The microscope photo of the pattern alignment is shown in Fig. 9, which illustrates the relative position of adjacent units in different areas. The tilt error is less than 0.0025°, and the relative position error is less than 5 μm. As the length of each unit is 300 μm, this alignment precision meets the response requirements of the sensor.

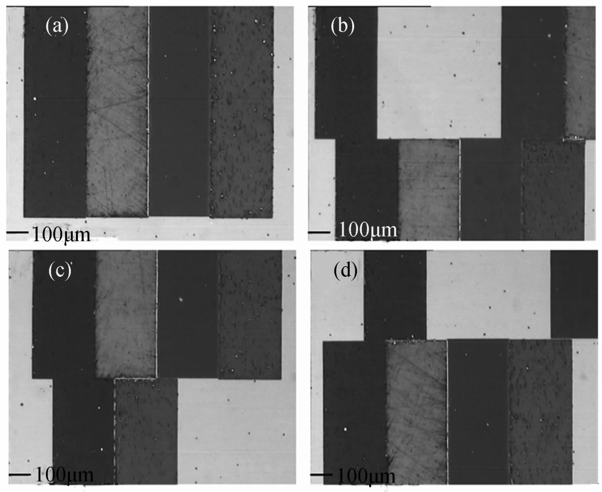

Fig. 9 The microscope photos of DEGR after UV aligning lithography. (a)～(d) are the randomly selected areas on the 100 mm DEGR, and each color represents one kind of grating unit

The number of the blazed gratings of the DEGR is the number of the process cycles (Fig. 5). Repeated experiments show that the yield in one cycle exceeds 95%, and the master DEGR maintained a good condition after replicated 20 times.

A laboratory testing of the signal response of the sensor with the DEGR (Fig. 7) has been conducted. The typical output spectrum of the DEGR is illustrated in Fig. 10. The spectra in Fig. 10(a)～(d) represent four continuous displacements. The signal response accuracy of the whole 150 displacements is 100%.

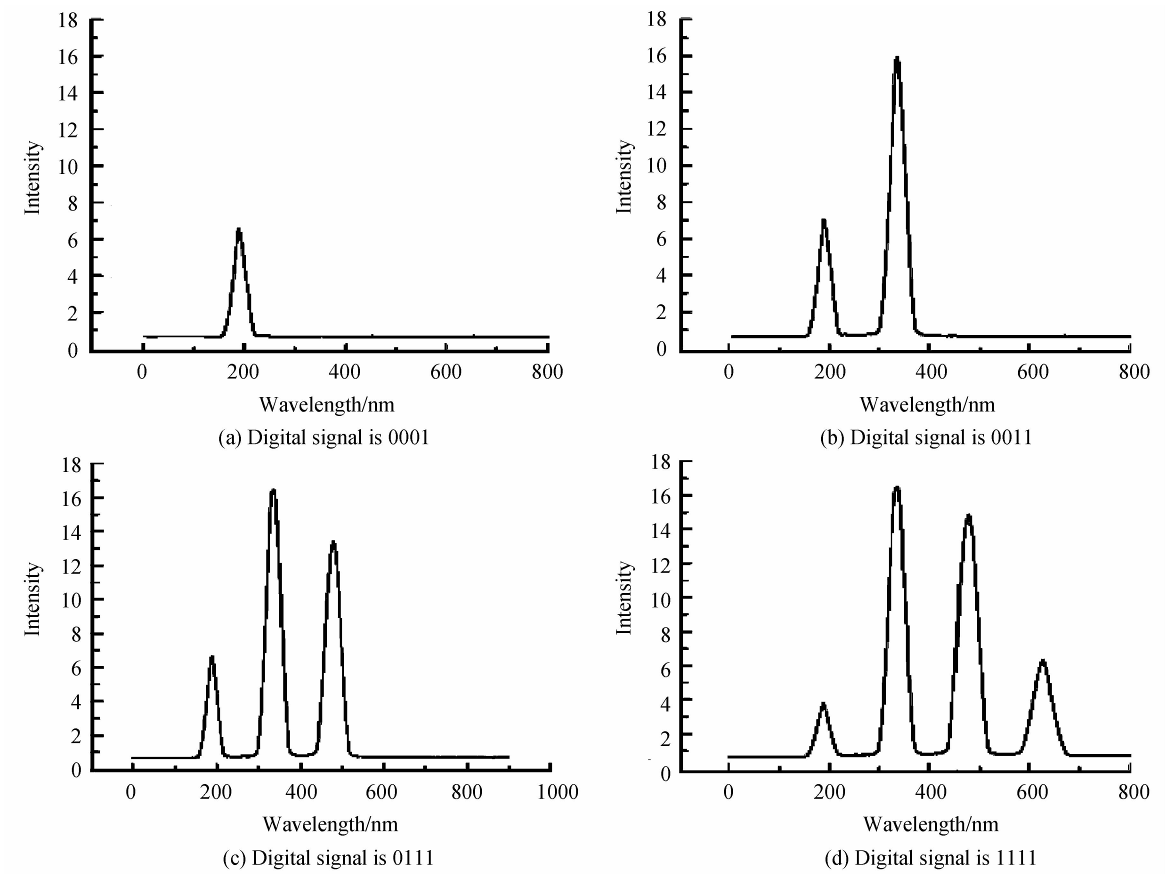

Fig. 10 Measured typical output spectra of the DEGR

4 Conclusion

A novel fabrication process of DEGR, which is used in digital wavelength encoding optical absolute displacement sensor, has been introduced. Experimental results show that the process which combines UV lithography, holographic lithography, wet etching and grating replication techniques, is highly repeatable. The replicated gratingswork properly in the ambient temperature ranging from −55℃ to 70℃, and its diffraction efficiency is higher than 90% of the master one. The fabrication precision meets the requirements of the optical sensor, and the signal response accuracy is nearly 100%. Moreover, this process could also be used to fabricate other micro-nanometer structures with high precision, complex pattern and poor working environment.

Another kind of DEGR contains 5 kinds of blazed grating units is under fabrication. Unit size is 300 μm while the length of the whole DEGR is 100 mm. This DEGR can perfectly meets the requirements of optical displacement sensor in aircraft control system. The results of laboratory bench test of the sensor will be reported in a future paper.

References

[1] FRITSCH K, BEHEIM G. Wavelength-division multiplexed digital optical position transducer[J]. *Optics Letters*, 1986, **11**(1):1-3.

[2] LIU Zheng-kun, XU Xiang-dong, ZHOU Qin, *et al*. Dual-reflector configuration in varied line-space grating displacement sensor[J]. *Review of Scientific Instruments*, 2008, **79**(4): 046105-1-3.

[3] MANWELL J,BAILEY G. An optical displacement transducer for aerospace applications[J]. *Sensors and Actuators A*, 1989, **18**(3-4): 233-237.

[4] MAGHOO M. A wavelength encoded rotary displacement fibersensor[J]. *Measurement Science and Technology*, 1994, **5**: 260-266.

[5] LACLAIR R D, SPILLMAN JR W B, KUHNS W W. Long stroke optical fiber linear position sensor for the FLASH program[C]. SPIE, 1996, **2840**: 137-141.

[6] ZHAO Li-xin, HU Song, WANG Zhao-zhi, *et al*. A novel fabrication of photoelectrical encoderby laser focus scanning fan-mask[J]. *Microfabrication Technology*, 2007, (6): 8-11.

[7] ZHANG Bing, ZHENG Pu-chao, ZHANG Chao, *et al*. A new type of displacement sensor test system based on Varied-line-space blazed grating[J]. *Transducer and Microsystem Technologies*, 2014, **33**(5): 80-83.

[8] LOU Jun, FU Shao-jun, LIU Zheng-kun, *et al*. Studyon positionsensorof holographic variable line-space plane gratings [J]. *Acta Photonica Sinica*, 2007, **36**(4): 655-658.