Magnetic Field Controlled Diffraction Grating

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Abstract— A novel magnetically tunable diffraction grating based on V-shaped and magnetic nanoparticles is proposed and demonstrated experimentally. The grating's period we made was 10 µm, and the grooves and the convex groove were both 5 µm. The refraction index of the ferrofluid is sensitive to surrounding magnetic field. We've demonstrated the magnetically tenability of this grating by measuring the changing of the diffraction angle of the high order diffraction light. The diffracted light was received by CCD and the movement of the laser spot, i.e., the small change of the diffraction angel was recorded. This approach is a good candidate for the following applications: magnetic sensors, magnetic controlled optical switches, modulator and so on.

1. INTRODUCTION

Diffraction gratings with periodic structures are very important optical spectral elements in optical system. The diffraction gratings are usually fabricated on the surface of planar substrate. Since the diffraction gratings is fixed and it is difficult to change the period. However in some cases, the diffraction property, i.e., the diffraction angle of a light beam with particular wavelength, is required to be adjustable. There's one device called acousto-optic modulator [1] is developed to fulfill this requirement. In this paper we have proposed another novel tunable diffraction grating with the help of the ferrofluid. Ferrofluid is a kind of stable colloidal suspension of ferromagnetic nanoparticles in a liquid carrier. These ferromagnetic colloids are usually dispersed by different kinds of surfactant [2]. This material can be applied to various modern technology fields, e.g., optical transmission [3], magneto-optical [4], optical switches [5] and thermo-optical [6, 7]. One of the most fascinating application of ferrofluid used as optical device should be MF tunable optical grating [8] and shows an increasingly important role in wide range of potential applications. Up to date, there are few reports on the magnetic field sensor based on tunable optical grating. Such research done by Shengli Pu et al. [9], they developed a MF grating with photoresist and ferromagnetic interphase and found that the transfer of the energy of the 0th-order diffracted light to that of the higher-order is apparent. Hongzhu Ji et al. [10] also investigated direction of the emergent light after the V-shaped groove filled with magnetic fluid which is related to the strength of the externally applied magnetic field.

In this paper, we have developed another tunable diffraction grating based on V-shaped groove filled with ferrofluid. When the strength of the around it changes we could clearly observe the change of the diffraction angle and the movement of diffraction light beams.

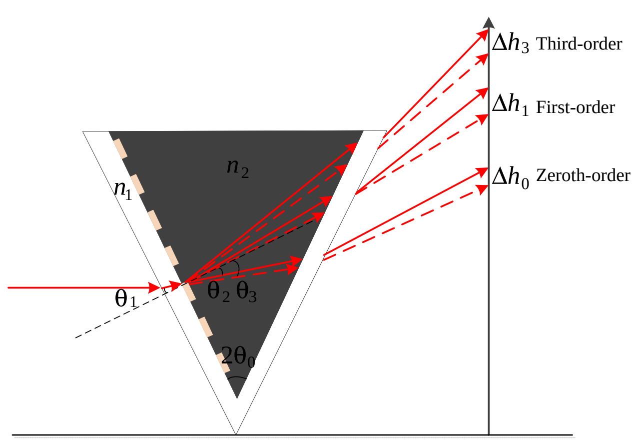


Figure 1: Schematic diagram.

2. THEORETICAL ANALYSIS

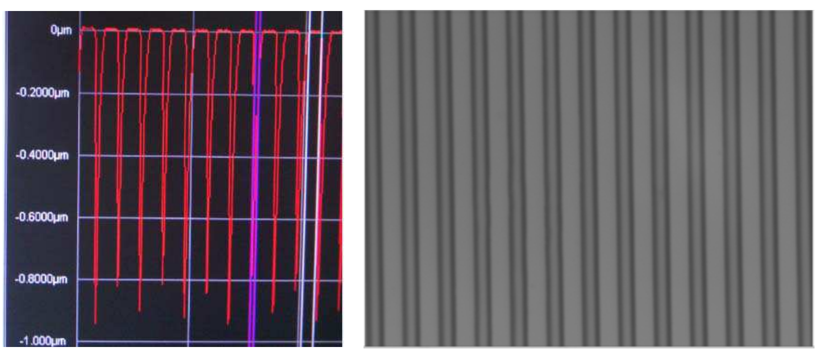
When the visible light incidence the diffraction grating, the light has the diffraction. It appears different order light. When they reach the ferrofluid's interface, they refract into the ferrofluid, for the different refraction index between glass and ferrofluid. As a result, there are diverse order lights, i.e., the zeroth-order, the first-order and the third-order and so on, displaying on the screen, as show solid line in Fig. 1. When we apply the external magnetic field, the refraction index of the ferrofluid changes consequently. The refraction angle transform θ_2 to θ_3, as showed in Fig. 1. The light path also changes from the solid line to the dotted line as showed in Fig. 1. They reach another position, and the distances are Δh_0, Δh_1, Δh_3, …, etc. which are the expression of the refraction angle change of different order light.

3. THE EXPERIMENT AND THE RESULTS

The grating is fabricated on a glass substrate which can transmit light well. In order to have better hydrophobicity, hexamethyldisilazane (HMDS) should be sprayed on the surface of the glass substrate. The photoresist used in this experiment is AZ5214e which is interchangeable from positive to negative sides. After being daubed on the glass substrate, with a speed of 2000 rounds per second, photoresist would be evenly distributed. Heated to be solid and covered with a mask plate, photoresist will then be explored to UV light whose period is 10 µm, after which, it would be etched in solution and turn into a thin grating with 1 µm depth as shown in Fig. 2(a) and a 10 µm cycle as shown in Fig. 2(b).

The ferrofluid we use in the experiment is EMG 900 produced by the Ferrotec (USA) Corporation. This ferrofluid is oil-based magnetic fluid whose average particle size is 10 nm, viscosity is 60 cP at 27°C, volume concentration of magnetite is 9%, density is 1.74 g/ml at 25°C and saturation Magnetization (Ms) is 990 Gauss [11]. The refractive index of EMG 900 is estimated to be around 1.65 ± 0.02 [12].

The system setup is shown in Fig. 3. A semiconductor laser diode whose wavelength is 650 nm is applied as the light source in this experiment. The laser light goes through a small hole and becomes



(a) (b)

Figure 2: The measured drawing of the diffraction grating. (a) The depth of the diffraction grating is about 1 µm. (b) The period of the diffraction grating is about 10 µm.

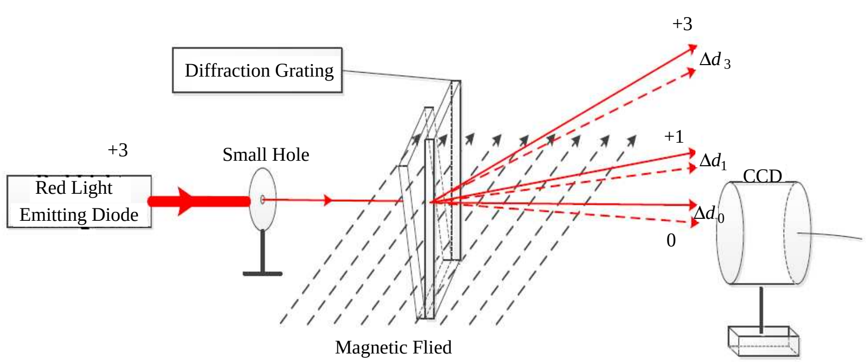


Figure 3: The experimental setup.

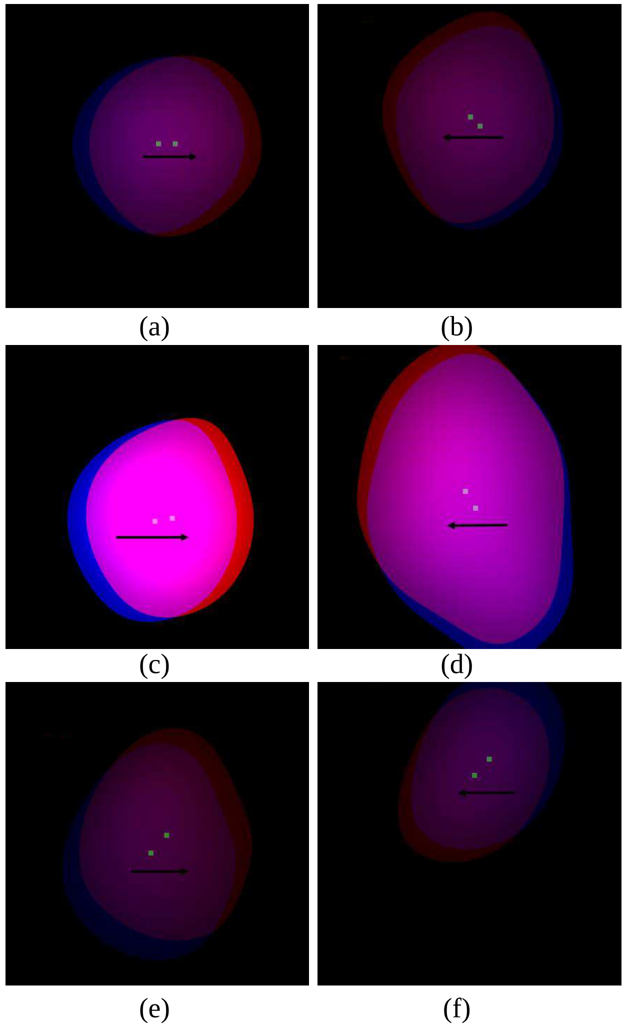


Figure 4: (a) and (b) is the experimental phenomenology of zeroth-order light, (c) and (d) is the experimental phenomenology of first-order light, (e) and (f) is the experimental phenomenology of third-order light.

thin and small. The thinner light will be perpendicular to the electrical field and the diffraction grating on the right. It diffracts in the diffraction grating, reflecting into the filling ferrofluid in the V-shaped grating. With an external magnetic field, the refractive index of ferrofluid will change, and the diffracting angle would be also varied accordingly. Consequently, the position recorded by the CCD shifts. The distance between CCD and grating sample is about 1 m. No matter the strength of magnetic increases or decreases, the diffracting angle will change so that the light spot also keeps alterative.

Without applying the external magnetic field, the position of the zeroth-order light was recorded in the blue spot as showed in Fig. 4(a). However, the spot moves toward the right side to the position of the red one shown in Fig. 4(a) when placing an 1000 Oe external magnetic field. The green spot is the midpoint of the blue and red ones. It is obvious that the green spot moves to the right after applying the external magnetic field. In addition, when the external of the magnetic field decreased from 1000 Oe to 0 Oe, the light spot moves back to the left as showed in Fig. 4(b). Similarly, with the same method and the same process the positions of the first-order and the third-order light spots are showed as Fig. 4(c), Fig. 4(d), Fig. 4(e), Fig. 4(f). The shift distance (the variety of the angle) is a little longer from the zeroth-order light to the third-order light. The changes of distance that the light spots move i.e., the shifts of reflecting angle is becoming lager and lager from the zeroth to third one. Furthermore, the first degree light owns the greatest diffraction efficiency, so we cannot make use of the higher degree light infinitely.

4. CONCLUSIONS

In summary, the diffraction grating with V-shaped groove based on ferrofluid has been analyzed theoretically and experimentally. It is the tunable diffraction grating by the strength of the external magnetic field, which characteristics is studied experimentally. This approach is a good candidate for the following applications: magnetic sensors, magnetic controlled optical switches, modulator and so on. This is a new method to fabricate the magnetically tunable diffraction grating. Compared with some other present diffraction grating, the proposed magnetically tunable diffraction grating has simple configuration and is easier to be produced. The period of this magnetically diffraction grating can be tuned to adapt to the different application by adjusting the strength of the external magnetic field. All of these are in favor of its practical applications.

ACKNOWLEDGMENT

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REFERENCES

1. Corey, R., A. Schmidt, and P. Saulnier, "Using a moving diffraction grating to simulate the function of an acousto-optic modulator," *American Journal of Physics*, Vol. 64, No. 5, 614–617, 1996.
2. Rosensweig, R. E., *Ferrohydrodynamics*, Courier Dover Publications, 2013.
3. Yang, S., Y. Chiu, B. Jeang, et al., "Origin of field-dependent optical transmission of magnetic fluid films," *Applied Physics Letters*, Vol. 79, No. 15, 2372–2374, 2001.
4. Du, T. and W. Luo, "Dynamic interference patterns from ferrofluids," *Modern Physics Letters B*, Vol. 9, No. 25, 1643–1647, 1995.
5. Gu, Y., G. Valentino, and E. Mongeau, "Ferrofluid-based reconfigurable optofluidic switches for integrated sensing and digital data storage," *Applied Optics*, Vol. 53, No. 4, 537–543, 2014.
6. Du, T. and W. Luo, "Nonlinear optical effects in ferrofluids induced by temperature and concentration cross coupling," *Applied Physics Letters*, Vol. 72, No. 3, 272–274, 1998.
7. Pu, S., X. Chen, W. Liao, et al., "Laser self-induced thermo-optical effects in a magnetic fluid," *Journal of Applied Physics*, Vol. 96, No. 10, 5930–5932, 2004.
8. Hong, C.-Y., H. Horng, I. Jang, et al., "Magneto-chromatic effects of tunable magnetic fluid grating," *Journal of Applied Physics*, Vol. 83, No. 11, 6771–6773, 1998.
9. Pu, S., X. Chen, L. Chen, et al., "Tunable magnetic fluid grating by applying a magnetic field," *Applied Physics Letters*, Vol. 87, No. 2, 021901, 2005.
10. Ji, H., S. Pu, X. Wang, et al., "Magnetic field sensing based on V-shaped groove filled with magnetic fluids," *Applied Optics*, Vol. 51, No. 8, 1010–1020, 2012.
11. Arce-Diego, J. L., R. López-Ruisánchez, J. M. López-Higuera, et al., "Fiber Bragg grating as an optical filter tuned by a magnetic field," *Optics Letters*, Vol. 2, No. 9, 603–605, 1997.
12. Konstantaki, M., A. Candiani, and S. Pissadakis, "Optical fibre long period grating spectral actuators utilizing ferrofluids as outclading overlayers," *Journal of the European Optical Society — Rapid Publications*, Vol. 6, 2011.