A Tunable Dispersive Optical System

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ABSTRACT

In this paper, two novel dispersive optical systems based on one (and more than one) grating(s) are presented, in which such grating(s) can be linearly modulated, i.e., translated linearly alone the propagation direction of the incident light. Moreover, a method, in which an order sorting filter is not required to separate the light of a selected order from the rest of the unwanted overlapping order, is also proposed here. The preliminary fabrication results reveals that all the components in the proposed design are possible to be realized. The dispersion testing also demonstrates that light can be diffracted and tuned by the proposed tunable-grating system.

Keywords: pitch-tunable grating, dispersive, linearly modulated, order sorting filter

1 INTRODUCTION

A grating consists of a plurality of periodic teeth as shown in Fig. 1. The light illuminated on the grating can be diffracted to different angles predicted by the basic grating equation [1] as follows:

$$d(\sin(\alpha)+\sin(\beta)) = m\lambda \qquad (1)$$

where d represents the pitch of the grating, α the incident angle, β the diffraction angle, m the diffraction order, and λ the wavelength. Consequently, the grating serves as a spatial filter. In eq. (1), given fixed α, β, and m, λ is proportional to d, meaning that varying d makes λ modulated. A grating which performs such modulation is called a pitch-tunable grating. An application of such gratings can be found in a monochromator, in which the diffracted light at the diffraction angle β is focused and projected onto a detector.

Pitch-tunable gratings can find many applications and have been widely investigated [2-4]. Most of them are composed of a grating part and spring flexures. By applying a force to deform the spring flexures, the pitch of the grating part will be tuned correspondingly. Due to the restriction of limited line-width during process, however, the pitches of these pitch-tunable gratings are often larger than 10μm. As a result, they can only be operated in the infrared regime instead of the visible regime. In addition, the existing pitch-tunable gratings are limited to out-of plane type, which increase the cost for alignment and assembly. Instead, an in-plane type can built more micro optical components as well as gratings together, thus reducing the cost required. However, several problems can still be found in designing this type of tunable gratings. One of the problems in such gratings is that the gap between teeth increases with pitch d. As a result, only a small portion of incident light contributes to the light collected by the detector, thus reducing the diffraction efficiency significantly for a large value of d. Another problem can be seen in eq. (1). With a given set of d and α, the same diffraction angle β will be caused in case the product of m and λ remains the same. For instance, a light of λ=400 nm and m=2 provides the same β as that of λ=800 nm and m=1. A conventional way to separate λ=400 nm from λ=800 nm in the above case is to utilize an order sorting filter. However, the filter in the scale of hundreds of microns is hardly available. In addition, the alignment is also not an easy task.

A novel way to overcome these problems is discussed in this work, including increasing the light efficiency during modulating and separating the overlapping light of different orders. In addition, the way to reduce the required number of teeth in the grating so as to remain the resolving power of the dispersive system will be detailed also. By combining these special designs, a miniaturized tunable dispersive optical system will be presented, which consisted of an in-plane type tunable-grating operated in the visible. A preliminary result for fabricating such micro device is also conducted to prove the feasibility of the designs.

2 PRINCIPLE

The novel design as shown in Fig. 2 is to overcome the loss of the incident light as modulating the grating. The diffracted light of m=1 is collected so as to obtain the maximum free spectral range (FSR) [1] as defined in eq. (2),

$$FSR = \lambda/m \qquad (2)$$

where λ is the initial wavelength over the spectral range of interest, and m is the diffraction order. The teeth of such grating can be movable linearly in parallel with the propagation direction of the incident light, thus varying the pitch d does not result in any change as "seen" by the incident light, meaning that the same amount of light illuminated on the grating is diffracted regardless of the values of gaps between the teeth. Unlike the case in the Fig.1, α and β are not constant when varying d; instead $\alpha-\beta$ remains unchanged for any values of d.

Another measure of estimating the performance of a grating is the resolving power (RP) [1] as defined in eq. (3),

$$RP = \lambda/\Delta\lambda = Nm \tag{3}$$

where N represents the number of the teeth, m the diffraction order, and $\Delta\lambda$ the minimum wavelength interval of two spectral components that are just resolvable by Rayleigh's criterion. In Fig. 2, m is set to be unity, meaning that N must be large so as to obtain a small value of $\Delta\lambda$, i.e., high resolution of the grating. However, usually a large N leads to more problems in the fabrications and operations.

A way to reduce the number of teeth while keeping RP the same as the case in Fig. 2 is shown in Fig. 3. Two gratings are disposed in such a way that the configuration of the 1st grating is similar to that in Fig. 2 except that the selected diffracted beam is of m>1, and the bulk of the diffracted light is further redirected to the 2nd grating at the same incident angle α and further diffracted at the same angle β as those in the 1st grating. In this configuration, RP as defined in eq. (3) is determined by the number of the teeth N_1 and the diffraction order m of the 1st grating. Thus, making m>1 leads to a smaller number of teeth than that required in Fig. 2 for the same value of RP. Moreover, a combination of two lenses and a slit (not drawn in scale in Fig. 3) serves as a beam expander by which the unwanted light diffracted at angles other than β from the 1st grating is eliminated. Owing to m>1, an overlapping occurs for multiple wavelengths, $\lambda, \lambda_1, \lambda_2, ..., \lambda/2, \ldots$ of different orders , m, m+1,…,2m,…, as expressed in eq. (4).

$$\begin{aligned} d_1(\sin(\alpha)+\sin(\beta)) &= m\lambda = (m+1)\lambda_1 = (m+2)\lambda_2 = \ldots \\ &= 2m\times\lambda/2 = \ldots = 3m\times\lambda/3 = \ldots \end{aligned} \tag{4}$$

If the beam of multiple wavelength is further directed to the 2nd grating with a different pitch d_2 from d_1, and the eq. (5) holds,

$$d_2(\sin(\alpha)+\sin(\beta)) = (m+1)\lambda \tag{5}$$

Then the different spectral components from λ are dispersed to different angles from β correspondingly by the 2nd grating. As a result, all the multiple spectral components are spatially separated from λ except for $\lambda/2, \lambda/3$….. Altogether, the light diffracted from the 1st grating is of diffraction order m, while the light diffracted by the 2nd grating is of order m+1. According to the ratio of eqs. (4) to (5), the following relationship exists.

$$p_1/p_2 = d_1/d_2 = m/(m+1) \tag{6}$$

Note that p_1 and p_2 are the pitches along the propagation directions of the incident light, rather than the grating lines, in the 1st and 2nd gratings, respectively. Equation (6) holds for any values of p_1 and p_2, meaning that p_1 and p_2 must be modulated simultaneously. The relationship between the detected wavelength and p_1 is as defined in the eqs.(7), (8) and (9).

$$n = \lambda/\lambda_0 \tag{7}$$

$$c = \alpha-\beta \tag{8}$$

$$p_1 = (n*p_{10}*(1+\cos(c))-h_1*\sin(c)*(n-1))/(1+\cos(c)) \tag{9}$$

where λ_0 denotes the wavelength detected initially during modulation, c the difference between the angles of incidence and diffraction, which remains a constant when modulating the pitches, h_1 the difference of heights between adjacent teeth in the 1st grating, and p_{10} the corresponding pitch of the 1st grating initially along the propagation direction of the incident light.

The relative diffraction efficiency of a case is shown in Fig. 4, in which m=5, the initial values of d_1 and p_1 are 7.21μ and 6μ, respectively, and the corresponding light initially collected is at 400 nm. As stated above, an order sorting filter is not required in the design here. It is as shown in the Fig. 5 and explained as follows. Taking p_1=8μ for instance, the light of wavelength λ=400 nm accompanies that of λ=800 nm. In this case, the collected power of λ=400 nm is the same as that of the case at p_1=6μ. Then the spectral component at λ=800 nm can obtained if the power detected at the case p_1=6μ is subtracted from that in the case p_1=8μ, resulting in the elimination of an order sorting filter to separate the energy of λ=800 nm from λ=400 nm. This method can be applied to not only the configuration in Fig. 3 but also in Fig. 2.

3 FABRICATION

This work proposed several designs to overcome the problems of an in-plane tunable grating. To verify the feasibilities in realizing these designs, the related micro fabrication process and testing experiments were performed. Fig. 6 shows the current fabrication results of a miniaturized disperse optical system for the visible regime. DRIE is used to simultaneously pattern the required components on a SOI wafer, including micro mirrors, a micro aperture, an actuator, and a pitch-tunable grating. Only one mask is required in the fabrication process, so that the alignment problem can be minimized. Fig. 7 shows the close view of the pitch-tunable grating. The blaze angle can be clearly observed. The sidewall with slight ripples is caused by the DRIE, and can be reduced by introducing a post oxidation process. The required micro cylindrical lens shown in Fig.3 can further be realized by introducing an extra mask, which has been demonstrated in our previous work [5]. Accordingly, all of the components in the design shown in Fig.3 are possible to be realized.

The captured images of pitch-tunable grating under actuating are shown in Fig. 8, where a micro V-beam thermal actuator is used to apply the required force. From the results, it is proved that the pitch-tunable grating can remain its periodicity during actuating. In the case of Fig. 8, the required driving current for a 50μm displacement is about 150 mA. The dispersion test was performed using an incident light beam at 532nm. From the captured grating spectra shown in Fig.9, the dispersion of a tunable-grating system can clearly be observed. By increasing the tuning voltages, the spectra shifted correspondingly and maintained approximately the same light intensity. To reduce the stray light and achieve better optical performance, an improved process to obtain a smoother grating sidewall is under developing.

4 CONCLUSIONS

In this paper, a novel tunable grating is presented, which is linearly modulated in parallel with the propagation direction of the incident light. Thus the incident energy almost fully contributes to the collected light. Moreover, two gratings are disposed in such a way that each grating requires less number of teeth than that required in the single grating configuration. Also in these two cases, an order sorting filter is not required to separate the spectral components of overlapping wavelength, provided that a simple mathematic operation is performed. The preliminary fabrication results show that all the components in the proposed design are possible to be realized. The dispersion testing also has been performed, which has successfully demonstrated the expected diffraction effect. It is believed that a more compact, low cost and miniaturized dispersive optical system can be realized by successfully integrating such designs and components.

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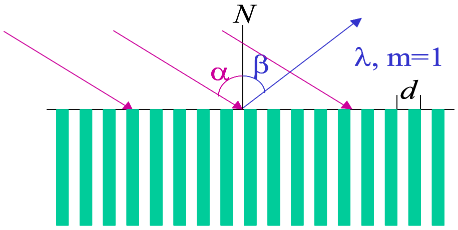

Fig. 1 A conventional tunable grating.

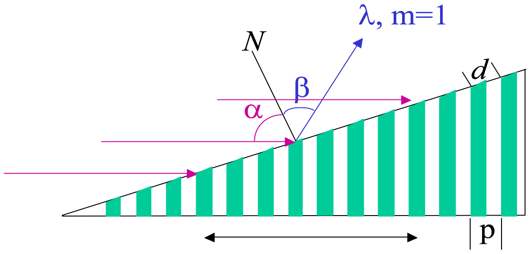

Fig. 2. A novel tunable grating (one grating configuration, m=1)

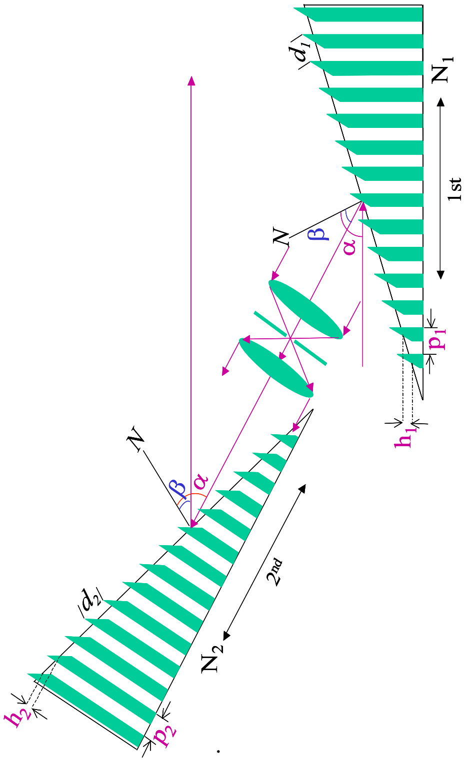

Fig. 3. The two grating configuration

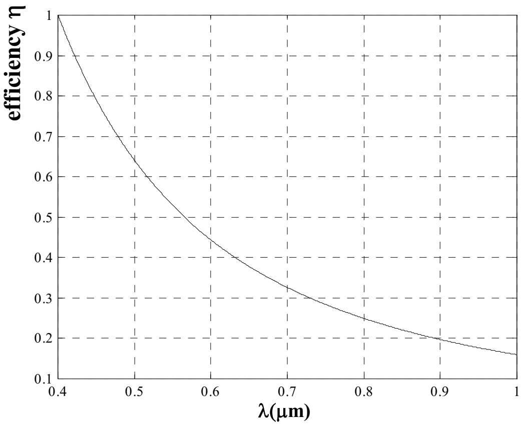

Fig. 4. The plot of efficiency η as a function of lambda λ in Fig. 3.

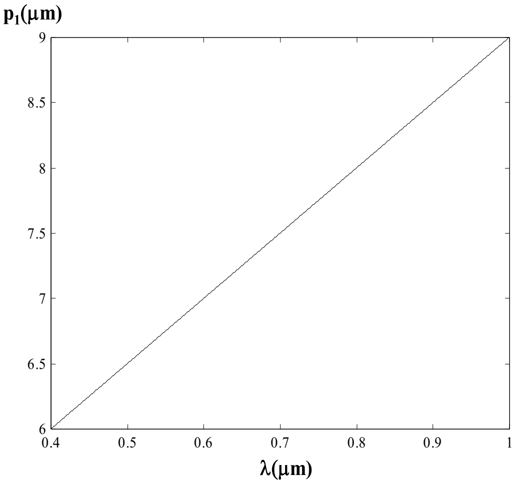

Fig. 5. The plot of the collected wavelength λ as a function of the ptich , p_1 ,in the 1st grating in Fig. 3.

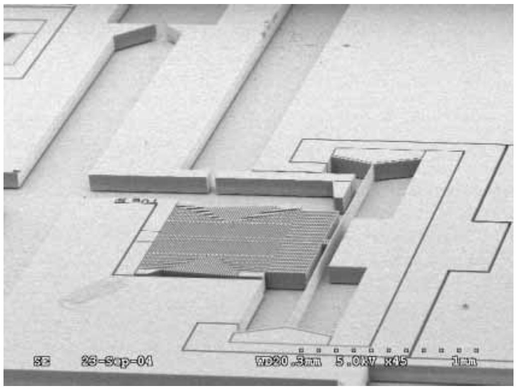

Fig. 6. Fabrication result of a tunable grating system.

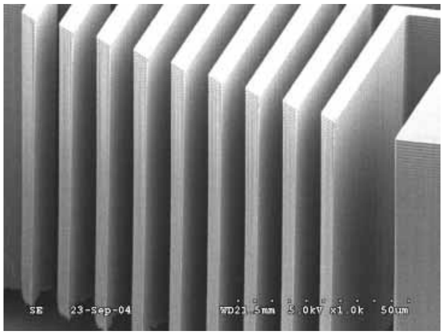

Fig. 7. Close view of the pitch-tunable grating.

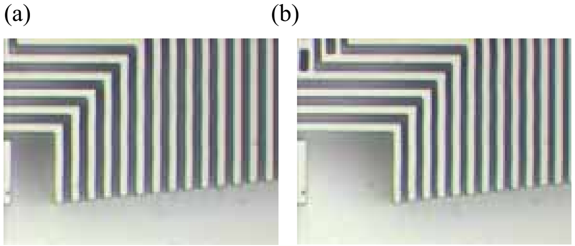

Fig. 8. The captured images of a pitch-tunable grating under actuating (a) with small driving current (b) with large driving current.

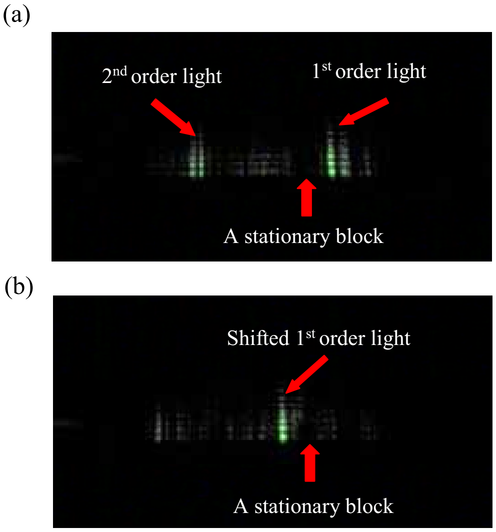

Fig.9. The captured grating spectra in testing the dispersion of a tunable-grating system (a) original state (b) under tuning.