Microelectronic Engineering 113 (2014) 74–79

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Short Note

A high-efficiency multi-beam splitter for optical pickups using ultra-precision manufacturing

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ARTICLE INFO

Article history:
Received 4 October 2012
Received in revised form 27 June 2013
Accepted 19 July 2013
Available online 27 July 2013

Keywords:
Beam splitters
Diffraction gratings
Optical data storage
Ultra-precision manufacturing

ABSTRACT

In this paper, we propose a compact seven-port beam splitter grating (BSG), based on a novel double-groove structure. The parameters of the grating are investigated by Fourier expansion and gradient algorithm. For an incident beam with TE mode normally passing through this BSG, high efficiency of 91.81% energy is theoretically split into the $-3T \sim +3T$ orders. The proposed double-groove blazed grating is fabricated using ultra-precision manufacturing. Therefore, the double-groove structure holds a high potential for mass production. The deviation of measured results from the simulated values is less than 3%, which proves that the experimental results are in good agreement with the theoretical values.

1. Introduction

An optical pickup (OPU) with a single laser beam for sequential data retrieving is used in conventional CD and DVD drives, in which the retrieved data rate is proportional to the rotation speed of the spindle motor. However, the maximum rotation speed is confined by the frequency response of the objective lens actuator. Using multi-beam in parallel is a straightforward solution to increase the data rate. One of the widely used methods of generating multiple beams is using the diffractive optical elements (DOEs) [1]. A grating is used to split an illumination beam into a plurality of reading beams with equal intensities, which are then projected onto a plurality of tracks of the optical storage medium. From the aspect of fabrication method, several methods have been proposed to fabricate DOEs. Using photolithography to fabricate highly efficient DOEs requires several alignment steps, which easily suffer serious noise due to light scattering. Two more promising high precision methods are focused ion beam (FIB) [2] and electron beam lithography (EBL) [3]. However, they require high cost and are time-consuming, and are rarely used for commercial applications. We have demonstrated the blazed gratings applied in a novel optical pickup system using ultra-precision manufacturing in our previous work [5,6]. Today, ultra-precision machining generally means a remarkable precision of the tools, machines and controls down the nanometer range. According to Taniguchi [7], precision is a relative idea changing its meaning with the enduring pursuit for higher accuracy. This process can fabricate op element in the sub-micrometer range with nanometer-scale roughness. It holds a considerable potential for mass production of highly efficient DOEs for other optical systems as well. From the aspect of diffractive efficiency, a conventional binary grating provides an average of only 75% diffraction efficiency [4]. Wen et al. [3] designed a TE mode seven-port beam splitter under normal incidence based on a double-groove binary grating at the 635 nm wavelength, the average efficiency is around 85%. In this paper, a double-groove blazed grating fabricated with more reliable ultra-precision manufacturing process is proposed. In this design, high efficiency of 91.39% is theoretically split into the $-3T \sim +3T$ orders. The deviation of measured values from the simulation is less than 2%, which proves that the experimental results are in good agreement with the theoretical values.

2. Design of the seven-port beam splitter

2.1. Design of the double-groove blazed grating

The double-groove blazed grating is shown in Fig. 1, where a monochromatic TE-polarization plane wave is incident from air with an incident angle θ. In Fig. 1, λ is the wavelength, d is the grating period, h is the grating depth, and x_1, x_2, x_3, and x_4 are the corresponding distances. In this work, θ is equal to 0, and the Fourier expansion and gradient algorithm [10] are employed to optimize the grating parameters. The objective is to minimize the error

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http://dx.doi.org/10.1016/j.mee.2013.07.010

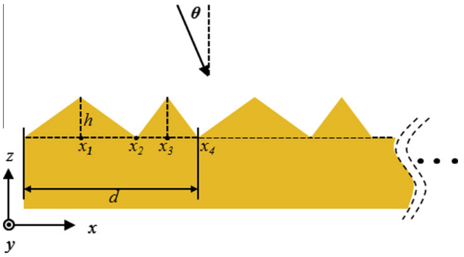

Fig. 1. Illustration of double-groove blazed grating.

function by selecting suitable grating parameters h, x_1, x_2, x_3. For the $(2n+1)$-port beam splitter, the error function is defined as the difference between the desired values of intensity in orders, and the calculated I_j, and is expressed as:

$$\varepsilon(x) = \sum_{j=-n}^{n}\left[I_j(x) - \hat{I}_j\right]^2 \tag{1}$$

The order intensities corresponding to the proposed model of Fourier coefficients in the decomposition of the grating transmittance are given by:

$$I_0(x) = \left(\frac{x_4}{N}\right)^2\left[\left(\cos\frac{\varphi}{N} + \cos\frac{2\varphi}{N} + \cdots \cos\varphi^2 + \sin\frac{\varphi}{N} + \sin\frac{2\varphi}{N} + \cdots \sin\varphi\right)^2\right] \tag{2}$$

$$I_j(x) = \left(\left|-\frac{L}{in\pi}\right|\right)^2\left(|A_1|^2 + |A_2|^2 + \cdots |A_{N-1}|^2\right)\sin^2\left(\frac{\varphi}{2N}\right) \quad j \neq 0, \quad j = \pm1, \pm2, \cdots \tag{3}$$

$$\begin{aligned} A_1 = {} & \exp\left(\frac{-in\pi}{L}\left(\frac{1}{N}x_1\right)\right) - \exp\left(\frac{-in\pi}{L}\left(\frac{1}{N}x_1 + \frac{N-1}{N}x_2\right)\right) \\ & + \exp\left(\frac{-in\pi}{L}\left(\frac{N-1}{N}x_2 + \frac{N}{N}x_3\right)\right) \\ & - \exp\left(\frac{-in\pi}{L}\left(\frac{1}{N}x_3 + \frac{N-1}{N}x_4\right)\right) \end{aligned}$$

$$\begin{aligned} A_2 = {} & \exp\left(\frac{-in\pi}{L}\left(\frac{2}{N}x_1\right)\right) - \exp\left(\frac{-in\pi}{L}\left(\frac{2}{N}x_1 + \frac{N-2}{N}x_2\right)\right) \\ & + \exp\left(\frac{-in\pi}{L}\left(\frac{N-2}{N}x_2 + \frac{2}{N}x_3\right)\right) \\ & - \exp\left(\frac{-in\pi}{L}\left(\frac{2}{N}x_3 + \frac{N-2}{N}x_4\right)\right) \end{aligned}$$

$$\begin{aligned} A_{N-1} = {} & \exp\left(\frac{-in\pi}{L}\left(\frac{N-1}{N}x_1\right)\right) - \exp\left(\frac{-in\pi}{L}\left(\frac{N-1}{N}x_1 + \frac{1}{N}x_2\right)\right) \\ & + \exp\left(\frac{-in\pi}{L}\left(\frac{1}{N}x_2 + \frac{N-1}{N}x_3\right)\right) \\ & - \exp\left(\frac{-in\pi}{L}\left(\frac{N-1}{N}x_3 + \frac{1}{N}x_4\right)\right) \end{aligned}$$

Table 1
Parameters of seven-port TE-polarization beam splitter gratings.

Beam splitter	λ	h	x_1	x_2	x_3	x_4	
	0.635	0.89	1.0915	2.183	6.0915	10	(unit: μm)

Here, the mathematical model is simply divided into N numbers of binary gratings. The Fourier series expansion is ranged in the interval [0, 2L]. I_0 is the intensity of the zero order; I_j is the intensity of jth order, and ϕ is the maximum phase of the interval.

The optimized parameters of double-groove blazed gratings are obtained for the seven-port TE-polarization beam splitter around the 635 nm wavelength (as listed in Table 1). The commercial software GSOLVER using numerical method of rigorous coupled wave analysis [8,9] is applied to predict the performance of gratings. The diffractive efficiencies obtained from our model and the software GSOLVER 5.1 are listed in Table 2 for comparison. In Table 2, the deviation of the two methods is less than 1.1%. Therefore, the profile of the double-groove blazed gratings can be quickly figured by the proposed model.

2.2. Fabrication analysis of double-groove blazed gratings with ultra-precision manufacturing

A number of algorithms for designing DOE's [10–12] have been proposed. For instance, rigorous coupled-wave analysis or finite domain time difference method is one of the most common used numerical tools. These methods may provide a better numerical solution for designing DOEs. However, it is difficult to fabricate DOEs with great precision, designed only from numerical solutions. Thus, in this study an effort has been made for optimizing the DOEs and analyzing the effect of fabrication error. The optical requirement of BSG is quite challenging, since the diffraction efficiency strongly depends on the grating profile. In fabrication, two single point diamond tools would be used sequently in cutting mold. In our test, changing different angles of diamond tools will cause a gap d_s, as illustrated in Fig. 2, between two types of triangular gratings. In order to reduce the fabrication error of d_s, a double-groove blazed grating of two isosceles triangles with different height is proposed and fabricated in this work. The simulated intensity distribution of designed double-groove blazed grating under various refractive indices is shown in Fig. 3, where the grating pitch is 10.45 μm. For an incident TE-mode beam with = 635 nm, the difference of diffraction angle between adjacent transmitted orders is about 3.484° derived by the grating equations [13]. The simulated efficiencies under various refractive indices are shown in Table 3. Since the optical signals from the track of the disk are converted into electric signals at the detector matrix, the non-uniformity simulated in Fig. 3 is acceptable if the signal-to-noise ratio matches the requirement. Besides, the non-uniformity among ±3, ±2, ±1, 0 orders can be compensated by the amplification of the photodiode IC (PDIC) or different current-to-voltage converter. Fig. 4 shows that the calculated diffraction efficiencies for the first ±3 under different gap d_s, from 0.1 to 0.8 μm, which will cause the unexpected asymmetric results of diffraction efficiency. Simulated results show that the alignment tolerance between the two cutting

Table 2
Comparison of diffraction efficiencies between two methods.

Beam splitter	−3rd	−2nd	−1st	0	+1st	+2nd	+3rd
Fourier expansion & Gradient algorithm	0.1036	0.1392	0.1092	0.1182	0.1092	0.1392	0.1036
GSOLVER	0.1007	0.1301	0.1194	0.1191	0.1194	0.1301	0.1007