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THE USE OF SOFT-LITHOGRAPHY TECHNIQUE ASSOCIATED WITH SEMICONDUCTOR LIGHT SOURCE FOR THE NEW OPTICAL DESIGN

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This study proposes a new type diffraction optics element (DOE) which combines semiconductor laser and polymer-based DOE processing technology into a single optoelectronic polymer device. To directly combine diffractive VCSEL (Vertical-Cavity Surface-Emitting Laser) with DOE, DOE surface profile can be integrated on the top of VCSEL utilizing polymer gratings by soft-lithography technique. Such a new type of polymer-based DOE-VCSEL can control spatial distribution of emitting laser energy and output angle. Taking the commercial DVD pickup head for example, this proposal combines discrete laser source and two optical elements into an integrated optical device, DOE-VCSEL, which can divide a single laser beam into three beams in different directions and control the angles and energy distribution of laser beams. Through the innovative development, it can be predicted that the optical loss and traveling distance are decreased by shrinking the device volume.

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1. Introduction

Recently, the rapid advancement in the development of semiconductor light sources and the continuous miniaturization process has made micro-optics one of the fastest developing fields of micro-technology. Among various kinds of micro-optical elements, diffractive optical elements (DOEs) are especially attractive because of their functional flexibilities in handling wave-front conversion as well as their planar, compact and lightweight natures which makes them suitable for integration with micro-electro-mechanical devices (MEMS) [1]. DOEs also have the nature advantages including low noise, large spatial bandwidth, parallel transmission of light, light-solving, light-gathering, and light-splitting capabilities. In spite of the rapid DOE development, still only a few methods demonstrate the potential to fulfill such high requirements [2]. The most advanced methods are based on the semiconductor processing technology and can be broadly divided into two major groups: (1) multi-mask binary method, sometimes referred to as binary optics [3] and (2) analog method [4].

In practical applications, polymer-based optical components have a great deal of promise for use in electro-optical devices, because polymers have some advantages, including light weight, cost-effectiveness and design freedom. There have been a number of reports on DOEs with

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formation of periodic structures on their surfaces [5]. However, these DOEs have disadvantages including low contact toughness and the need for a complex etching process. On the other hand, DOEs prepared inside polymers have greater toughness and are suitable for photonic three dimensional device integration.

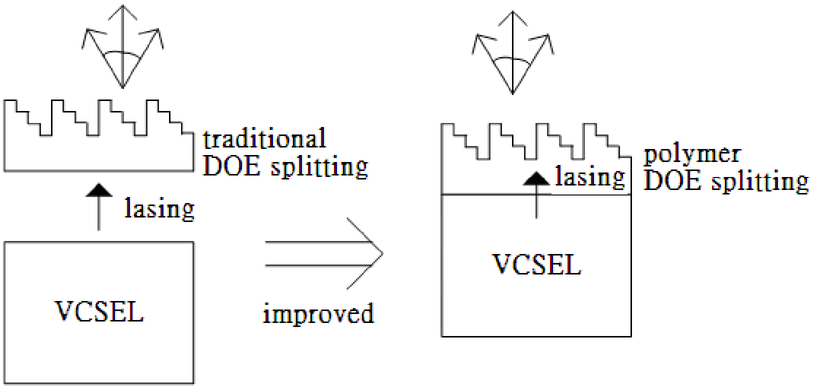


Fig.1. The improved polymer-based DOE in the proposed DOE-VCSEL structure.

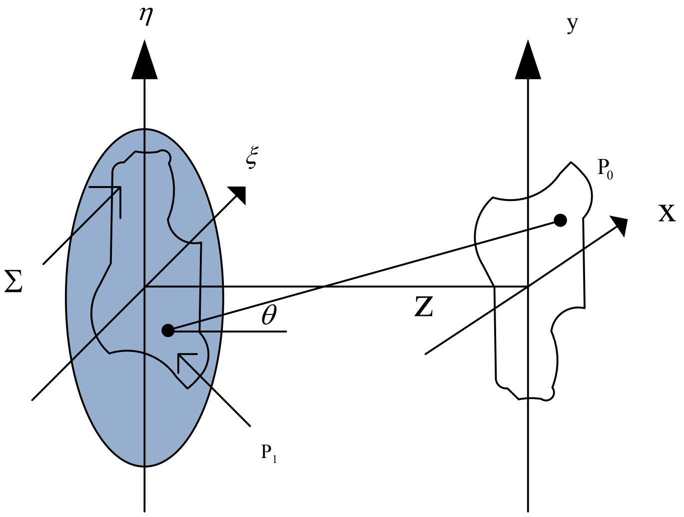


Fig.2. Schematic illustration of diffraction geometry.

Currently, there is a great technical interest in the development of new processing methods for the thin film fabrication to be employed in electro-optical devices. The purpose of this paper is to present a new fabrication technique, in which the polymer gratings are used for top pattern covering on the semiconductor light source (ex. VCSEL) [6]. In traditional design, the optical DOE is set up with the laser diode having a spacing between them as shown in the left of Fig.1. In this study, the traditional DOE is replaced by 3-order periodical polymer gratings which close compact on the VCSEL surface as shown in the right of Fig.1. In our opinion, this technology combines the method of using polymer gratings on the VCSEL to reduce light decay, shrink device length and enhance efficiency which is still limited in the literature. In addition, the use of coating surface gratings by polymer material on the VCSEL has many advantages including easy process, low cost and no additional technology in need.

2. Theoretical Analyses

The basic diffraction theory is briefly depicted as below. As shown in Fig.2, the diffracting aperture is assumed to place in the (ξ,η) plane and is shown in the +z direction. The wave field across the (x,y) plane which is parallel to the (ξ,η) plane at the normal z distance could be calculated. A simple and usable expression approximation for the distance r_{o1} between P_1 and P_0 is introduced. According to the Huygens-Fresnel principle, the aperture distribution can be expressed as [7]

$$U(P_0)=\frac{1}{j\lambda}\iint_{\Sigma} U(P_1)\frac{\exp(jkr_{01})}{r_{01}}\cos\theta ds \tag{1}$$

where θ is the angle between the outward normal and the vector from P_0 to P_1. The cos θ term is given by

$$\cos\theta = z/r_{01} \tag{2}$$

and the Huygens-Fresnel principle therefore can be rewritten as

$$U(x,y)=\frac{z}{j\lambda}\iint_{\Sigma} U(\xi,\eta)\frac{\exp(jkr_{01})}{r_{01}^2}d\xi d\eta \tag{3}$$

by introducing r_{o1} intro the eq.( ), the resulting U(x,y) field at (x,y) can be given as

$$U(x,y)=\frac{e^{jkz}}{j\lambda z}\int\int_{-\infty}^{\infty}U(\xi,\eta)\exp\left\{j\frac{k}{2z}\left[(x-\xi)^2+(y-\eta)^2\right]\right\}d\xi d\eta \tag{4}$$

where the finite limits of the aperture in the U(ξ,η) definition have been incorporated in accordance with the usual assumed boundary conditions.

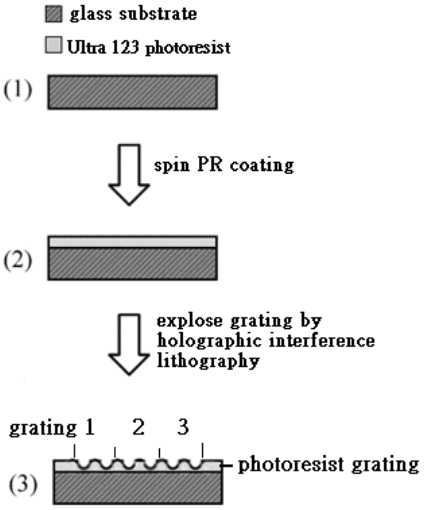


Fig.3. Schematic process of periodical photoresist grating.

In this study, the design principle is based on the binary Dammann phase fourier grating [8]. Through the Malab software calculation, the DOE profile on the outward surface can be predicted and applied on the top of VCSEL structure which will result in new splitting DOE-VCSEL structure. Dammann grating is assumed that the grating does not absorb the input light but modulate the light phase and therefore can enhance the efficiency of light diffraction. The typical binary Dammann grating can be used on the multi-beam splitting applications. The function of tunneling amplitude F(x) is expressed as

$$F(x) = \exp(i\phi(x)) \tag{5}$$

where the binary phase value φ (x) is either 0 or π and F(x) is 1 or -1.
then F(x) is rewritten as

$$F(x) = \sum_{n=-\infty}^{\infty} f(x)\delta(x-n) \tag{6}$$

According fourier transformation theorem f(x) is expressed as

$$f(x) = \sum_{n=-\infty}^{\infty} A(n)\exp(i2\pi xn) \tag{7}$$

If the input amplitude is assumed unity, the intensity of other orders can be regarded as the square of A(n), where the A(n) is expressed as

$$A(n) = \int_{-1/2}^{1/2} f(x)\exp(i2\pi nx)dx \tag{8}$$

$$A(n) = i\left[(-1)^N \operatorname{cosc}(n) - 2\sum_{k=1}^{N}(-1)^k 2x_k \operatorname{cosc}(2x_k n)\right] \tag{9}$$

According the above equations, the adjustable intensity can be expected if the phase transition point is changed.

3. Experimental

To date, there are many studies of discussion about promoting DOE efficiency. A promising approach for the fabrication of continuous phase profiles is direct laser beam writing. At each (x,y) location, the exposure intensity is controlled according to the desired depth. Although the direct writing techniques seem quite promising, yet it suffer from several disadvantages, mainly from the long term fabrication period and the system complexity.

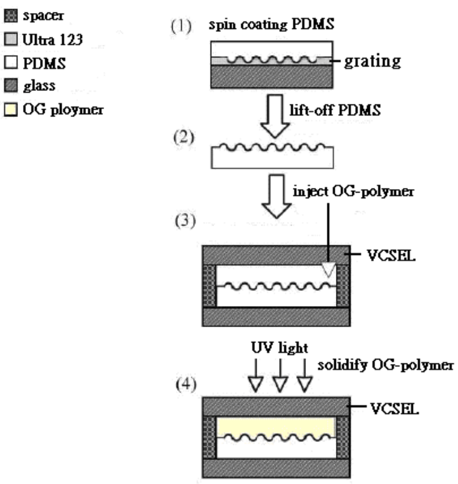


Fig.4. Schematic process of transferring polymer gratings to reprint on the VCSEL.

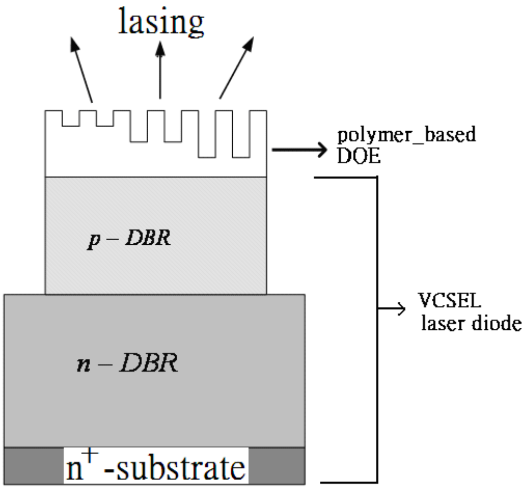
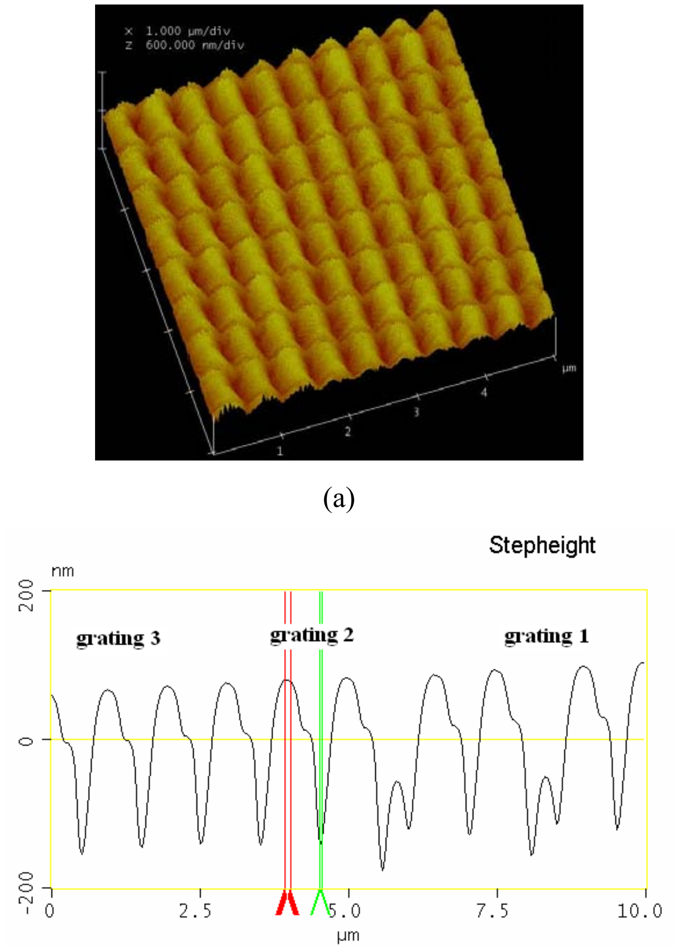


Fig.5. Final polymer-based DOE-VCSEL device.



(a)

(b)

Fig.6. (a) 3D Surface polymer gratings under AFM measurement. (b) Step height of three different gratings under AFM measurement.

In this research, the soft-lithography and optics interferences techniques are used to make a layer of polymer grating on the VCSEL. By this way, it does not change anything of the VCSEL but uses the character of Dammann grating to split laser light which is output from the VCSEL. This research uses high polymer material to produce diffractive-mode grating elements. There are many merits for the high polymer material in this study that is, adjustable reflecting rate, good light-transmitting, heat stability. The experimental process in this work indicates how to make the sharp outward high polymer gratings on VCSEL substrate [9,10]. Step 1: using holographic interferometry technology to fabricate the diffractive-mode gratings. First, the glass is used to be the substrate of diffractive grating, and spin positive photo-resist (Ultral 123) on the substrate. The lithographic photo-resist process flow is shown in Figure 3. In the experiment, a He-Cd laser with a wavelength of 325 nm and the power of 60mW is used in a holographic interferometry technology system. The laser beam is divided into two same beams by beam splitter. These two waves travel on the cross direction and meanwhile they interfere with each other and form the pattern of reflecting grating on the sample. The relation between diffractive grating period T, the incident angle of light θ□ and θ_2 and laser wavelength λ, respectively is given in equation (10).

$$T = \frac{\lambda}{\sin\theta_1 + \sin\theta_2} \tag{10}$$

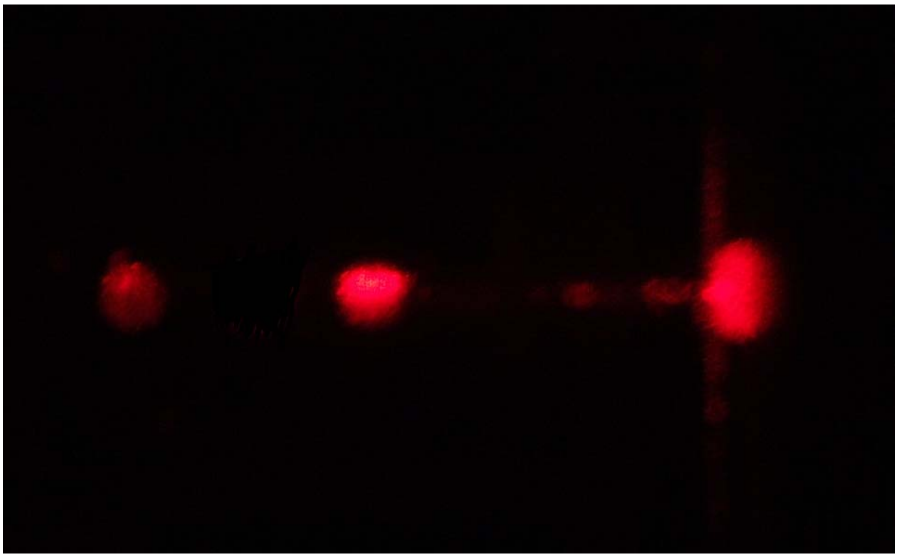


Fig.7. Raman diffraction pattern of the proposed polymer gratings.

The grating depth can be determined by the intensity of He-Cd laser. The final three different depths of polymer gratings are also depicted in Figure 3. Step 2: To reprint the gratings on the VCSEL substrate. The high polymer (Poly dimethyl siloxane, PDMS) is used to reprint. We spin thin film of PDMS on the photo-resist substrate which has the sensibility of diffractive grating. Because of the characteristic of PDMS, we can easily separate them. After separation, the stripe pattern of grating is transmitted on PDMS thin film. And we can also transmit the patter from PDMS thin film into high polymer substrate. First, we take PDMS thin film and put it on glass substrate, and then, we put two boards on each side of the substrate. Next, we place a glass substrate over it. After these steps, PDMS thin film is placed between two glass substrates, and there will be a revealed interval inside. After that, we fill OG into the middle of the two glasses, and then OG will adhere on the model. OG is a sensitive polymer material; the UV light is then applied to solidify it. At last, the reflecting gratings are produced on the VCSEL substrate. The total processing procedures and final DOE-VCSEL device are schematically shown in the Figure 4 and 5, respectively. The attempt of introducing gratings by the interference of two beams holography is simple and first investigated in the literature.

4. Results and discussion

First, the experimental polymer gratings used as polymer-based DOE with three different depths have been fabricated and the 3D AFM morphology is shown in Fig.6(a). The observed rough surface is resulted from the shift in the He-Cd laser exposure and the obvious boundary is the interface between two gratings. From Fig.6(b), the observable three different periodical gratings are revealed and marked with grating 1, 2 and 3, respectively. The average grating depths are 237.21nm, 219.10nm and 209.54nm, respectively in the preliminary experiment. The optimal process for the proposed polymer-based DOE is still under proceeding. Second, another test is executed, i.e., the Raman diffraction measurement. According to the Raman principle, the screen will appear three light spots and noted as 0, +1 and -1 orders, respectively. In experiment, the He-Cd laser is used to input onto the polymer gratings and the final Raman diffraction pattern is clearly shown in Fig.7. The diffraction angle is measured to be the value of 42.36^0. After measuring the individual spot power and the distance between screen and spot, the period of the polymer then can be calculated by eq.(11)

$$T = \frac{m\lambda}{\sin\theta} \tag{11}$$

Thus, the calculated period is 0.493um which is also compared to the measured period. The deviation in polymer period between calculation and measurement is less than 7.52nm.

5. Conclusions

DOE plays a major role in various optical applications such as read/write heads in DVD. Most of these topics are still open for searching the better design. In this study, a concept of polymer-based DOE-VCSEL is proposed and the preliminary DOE results shown the possible application in the future while polymer DOE combined with VCSEL by soft-lithography technique. The experiments confirm the high resolution and accuracy of the method for both pattern and profile forming, which indicate a high potential of the presented technology for fabricating diffractive optical elements with high diffraction efficiency. In comparison to other methods, in turn, allows for a much better control of the phase profile and ensures larger process tolerances.

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