Grating light modulator for projection display

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A novel grating light modulator for projection display is introduced. It consists of an upper moveable grating, a bottom mirror, and four supporting posts between them. The moveable grating and the bottom mirror compose a phase grating whose phase difference is controlled by the actuating voltage. When the phase difference is $2k\pi$, the grating light modulator will switch the incident light to zero-order diffraction; when the phase difference is $(2k-1)\pi$, the grating light modulator will diffract light to first-order diffraction. A 16×16 modulator array is fabricated by the surface micromachining technology. The device works well when it is actuated by a voltage with 1-kHz frequency and 10-V amplitude. The fabricated grating light modulator can show blackness and brightness when controlled by the voltage. This modulator has potential applications in projection display system.

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Optical micro-electro-mechanical system (optical MEMS or MOEMS) technology has experienced rapid progress in recent years. MEMS-based light modulator for display has become one of the research focuses[1−3]. Compared with the traditional projection light valve, MEMS-based light modulators are lighter than cathode ray tube (CRT), and have faster response frequency than liquid crystal display (LCD). Digital micro-mirror device (DMD)[4] developed by Texas Instruments is a successful example of optical MEMS device, which has great influence on modern display apparatus. The DMD consists of an array of moveable micro-mirrors. Actuating voltage controls the mirror's tilt angle electro-statically in a binary fashion, and then the incident light is reflected and modulated by the tilt mirror. Another optical MEMS based light modulator designed for projection display is grating light valve (GLV)[5]. The GLV is composed of an array of phase gratings which can switch light from zero diffraction order to first diffraction order by controlling the phase difference electrically. The GLV has relatively simple structure and can be actuated faster than DMD, but it is a linear array light modulator, and additional fast scanning setup is used to produce a two-dimensional (2D) image. In this letter, we introduce a novel grating light modulator (GLM)[6,7] which is also based on phase grating but can compose 2D modulator arrays easily. With 2D modulator arrays, the scanning part is eliminated and the projection system will be simpler than that based on GLV. The grating light modulator has the fast response merit of GLV and the 2D array structure of DMD. It has promising applications in projection display.

The GLM consists of an upper moveable grating, a bottom mirror, and four supporting posts between them, as shown in Fig. 1. The upper moveable grating and the bottom mirror, which are both made up of aluminum, compose a phase grating. The grating constant d of the upper grating is 8 μm and the ribbon length L, ribbon width a, beam width, and anchor width of the grating are 48, 4, 4, and 4 μm, respectively. When light reaches the surface of the phase grating, it is reflected and diffracted. According to the Fourier optics theory, if the modulator is normally illuminated by a unit-amplitude, monochromatic plane wave, the field distribution on the surface of the upper grating is proportional to the transmittance function t_g of the modulator. If a low reflection layer is deposited on the surface of the support post, anchor, and beam, such as titanium and tungsten alloy, transmitting function of the GLM can be written as

$$t_g = \left[\sum_{m=-\infty}^{\infty} \text{rect}\left(\frac{x-md}{a}\right) + \exp\left(\frac{\text{j}4\pi h}{\lambda}\right)\sum_{m=-\infty}^{\infty} \text{rect}\left(\frac{x-md-d/2}{a}\right)\right] \times \text{rect}\left(\frac{x}{W}\right) rect\left(\frac{y}{L}\right), \tag{1}$$

where λ is the wavelength of the incident light, $2h/\lambda$ corresponds to the grating's phase difference, W is the width of the grating. The Fourier transform of t_g is:

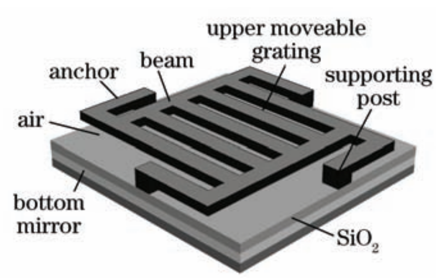

Fig. 1. Designed model of the single GLM.

$$T_g = \tilde{F}(t_g) = \frac{aLW}{d} \sin c(Lf_y) \times \sum_{n=-\infty}^{n=\infty} [1 + \exp(\frac{j4\pi h}{\lambda} + jn\pi)] \times \sin c(\frac{an}{d}) \sin c[W(f_x - \frac{n}{d})], \quad (2)$$

where $f_x = x/\lambda z$, $f_y = y/\lambda z$.

The intensity distribution of the diffraction light can be calculated with Eqs. (1) and (2) as

$$I_g(x,y) = |U_g(x,y)|^2 = \left| \frac{r}{\lambda z} T_g(\frac{x}{\lambda z}, \frac{y}{\lambda z}) \right|^2, \quad (3)$$

where r is the reflectivity of the upper grating.

Initially, the phase difference between the light beams reflected from the upper grating and the bottom mirror equals $2k\pi$ (k is an integer). After a voltage is applied on the modulator, the electrostatic force pulls the upper grating down and the phase difference of the GLM becomes $(2k-1)\pi$. Figure 2 illustrates the calculation results of the diffraction light distribution of GLM when the phase difference is π and 2π respectively[8,9]. It can be seen that when the phase difference is $2k\pi$, the incident light is diffracted to the zero-order diffraction, and when the phase difference is $2(k-1)\pi$, the incident light is diffracted to the first-order diffraction. So light can be switched between the first and the zero diffraction orders electro-statically. With an optical filter to only transmit the zero-order diffraction light, black or bright pixel can be achieved by projecting the light on a screen. When the phase difference of the GLM is $2(k-1)\pi$, there is a black pixel on the screen. On the contrary, when the phase difference is $2k\pi$, there is a bright pixel on the screen.

The GLM is fabricated with the surface micromachining technology[10]. The fabrication begins with a $\langle 100 \rangle$ p-type silicon wafer. For electrical isolation among bottom electrodes, thick thermal SiO_2 with the thickness of $500-600$ nm is deposited by furnace. Then a 100-nm-thick Al layer is thermally evaporated and patterned to form the bottom mirror and the bottom electrode. To avoid circuit-short when pull-in happens, a 280-nm-thick SiO_2 dielectric layer is deposited as protection layer by plasma enhanced chemical vapor deposition (PECVD). After the formation of SiO_2 layer, 600-nm-thick Al is sputtered and lithographed to form the support post. 600-nm-thick polyimide is then spin-coated as sacrifice layer which will form a 600-nm air gap after it is released at last. Next, a 100-nm-thick Al layer is evaporated and lithographed to form the upper moveable grating. Furthermore, 200-nm-thick titanium and tungsten alloy is evaporated and lithographed to cover the surrounding part of the upper moveable grating to reduce its surface reflectivity. Finally, the sacrifice layer is removed to form the air gap. Figure 3 illustrates the scanning electron microscopic (SEM) photograph of part of the fabricated 16×16 GLM array. Dimension of each single modulator is 52×52 (μm), width of the grating ribbon is 4 μm, and the designed initial phase difference is 10π (when the incident light wavelength is 530 nm).

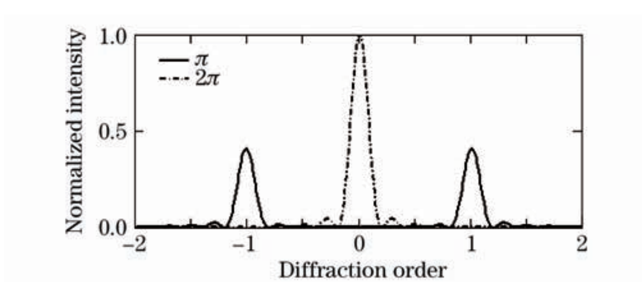

Fig. 2. Diffraction light distributions of the phase grating when the phase difference is π and 2π.

An experimental projection system (shown in Fig. 4) is set up to test the GLM's actuating characteristics. After the incident light is diffracted by the modulator, the first-order diffraction light is blocked by the filter, and the zero-order diffraction light passes the filter directly. The projection lens projects the zero-order diffraction light on a photodiode (PD) which is at the image plane of the GLM. To ensure that the detector receives only one modulator's light, the photosensitive area of the selected PD equals the image size of one GLM pixel. The phase difference of the GLM is switched between $2k\pi$ and $(2k-1)\pi$ by the voltage. When the phase difference is $2k\pi$, the PD receives light and the photocurrent is generated. The photocurrent is amplified by the current amplifier and then observed with an oscillograph. When the phase difference is $(2k-1)\pi$, no light reaches the PD and the oscillograph gets no signal. So, the GLM's response characteristic can be observed with the wave of the oscillograph. Figure 5 illustrates the modulator's response when it is actuated by the voltage of 1-kHz frequency and 10-V amplitude. It can be seen that the device works well when it is actuated by this voltage.

If we remove the PD and place a screen at the same position, the image of the GLM can be observed with the optical system. Figure 6 gives the experimental results of some GLM pixels' image. It can be seen that after the voltage is applied, the corresponding pixels' image turn from brightness to blackness.

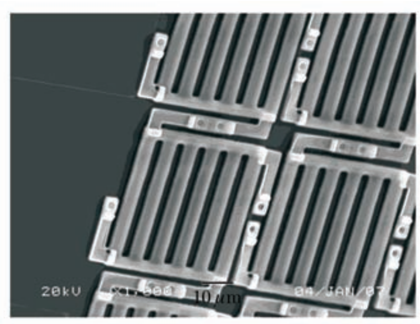

Fig. 3. SEM photograph of the fabricated GLM.

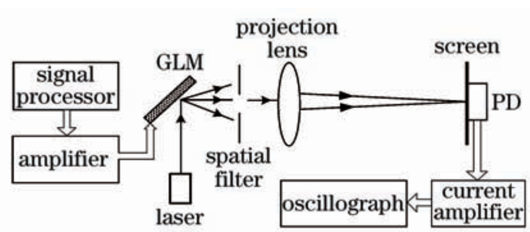

Fig. 4. Projection system based on GLM.

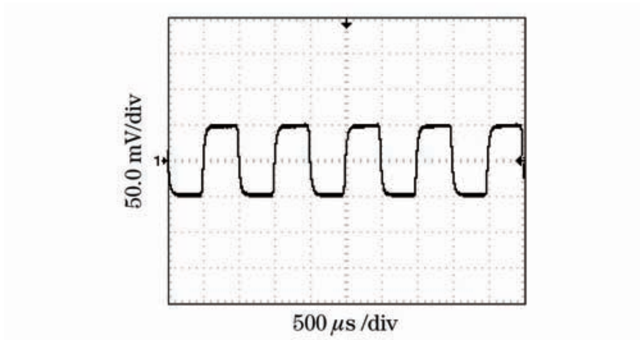

Fig. 5. GLM's response when actuated by the voltage of 1-kHz frequency and 10-V amplitude.

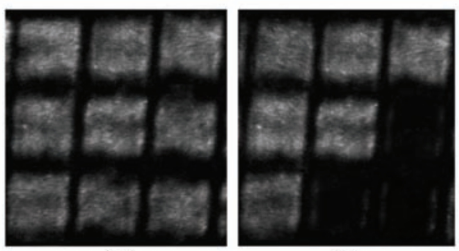

Fig. 6. Projection images of the GLM. (a) With no applied voltage; (b) after voltage is applied on the lower-right three pixels.

In conclusion, we have introduced a new type of 2D GLM which can switch light from the zero-order diffraction to the first-order diffraction by controlling the phase difference electro-statically. The device works well when it is driven by a voltage of 1-kHz frequency and 10-V amplitude. With the applied voltage, GLM can show brightness and blackness. This modulator has potential applications in projection display. Currently the fabricated device is 16×16 arrays driven by the passive actuation mode. When the fabrication process is stable, it is easy to fabricate the large area arrays with the active driving mode. An active driving method based on a complementary metal-oxide-semiconductor (CMOS) circuit will be utilized in the next fabrication.

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