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Fabrication of a 2D thermally tunable reflective grating for measuring a CO_2 laser beam profile

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In this article, application of a 2D thermally tunable reflective grating for measuring the beam profile of a CO_2 laser is proposed. A 2D grating is first fabricated on a glass substrate by conventional lithography technique. The grooves of the grating are filled with nitrobenzene, the refractive index of which highly depends on temperature. A double side polished silicon wafer is then placed on the grating. If a CO_2 laser is incoming from silicon side, a portion of it is transmitted and absorbed in the grating structure. Depending on the beam profile of the CO_2 laser, a temperature profile is produced on the grating causing the same profile for efficiency of the grating for a visible light. The changes in the efficiency, cause changes in intensity of diffraction orders. By measuring the intensity of the first order of diffraction, the beam profile of the CO_2 laser is imaged on a visible CCD camera.

Keywords: tunable grating, laser beam profiler.

1. Introduction

A tunable grating is a grating whose characteristics can be changed by an actuation method. A tunable diffractive grating has various applications in external cavity tunable lasers, modulators, optical switches, and micro-spectrometers [1]. In a tunable grating, different techniques are used to change the period or the efficiency of the grating.

In the period tuning case, by changing the period, the diffraction angle of an incident light is changed. The thermal actuation for optical modulation [2] and tuning of a fiber Bragg grating, are some examples of this kind of tuning technique. The piezoelectric actuation is also reported to change the period of a diffraction grating [3].

In another tuning case, the period of the grating is fixed, but the intensity of diffraction orders is changed. These kinds of gratings are called grating light valves (GLV). Different kinds of actuation techniques such as electric field actuation and thermal actuation are also used for this task. The electric field actuation method has been used to actuate an electro-optically controlled liquid crystal diffraction grating [3]. In another technique, in a MEMS based device, an electrostatic force causes tiny ribbons to be moved up and down to form a specular surface or a diffractive grating [4, 5].

The thermal method has also been used by our group to actuate a grating light valve [6, 7]. This kind of grating can be used to measure the beam profile of a CO_2 laser. At the moment, CCD and CMOS cameras are used for measuring the beam profile of visible and near infrared lasers. But for the far infrared region (like 10.6 μm for CO_2 laser), expensive Pyrocams, which use pyroelectric phenomenon for detection, are used. Thermally tunable gratings (TTG) can be used for measuring the beam profile of far infrared lasers.

In this article, a 2D thermally tunable reflective grating is used to measure the beam profile of a CO_2 laser. In the previous works as mentioned in Ref. [6], after each measurement time had to be taken for the grating to cool down and get ready for another measurement. But in this paper, a thermally tunable grating with fast response time has been reported, which makes the online measurements feasible.

The theory of the experiment is explained first by means of computer simulation. Then the fabrication method and experimental results are explained.

2. Theory

Consider a 2D square highly reflective grating as shown in Fig. 1. Suppose that the grating is made of a material with refractive index n_1 and the holes of the grating are filled with a material with refractive index n_2. As seen in Fig. 1, parameters a and b are the width of the lands and holes, respectively. We define the aspect ratio parameter as AR = $[a/(a + b)]\times 100$.

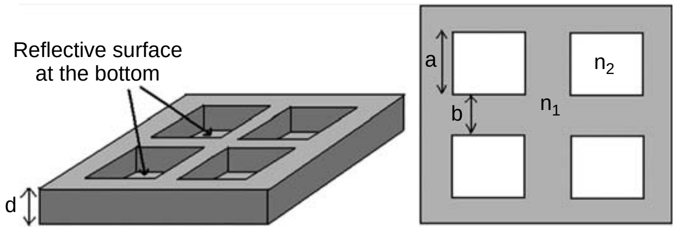

Fig. 1. Structure of a 2D reflective grating.

When a light beam is incident on the grating, a portion is reflected through the lands and a portion is reflected through the holes of the grating. The phase difference between these two portions is as follows

$$\gamma = \frac{2\pi}{\lambda}(n_1 - n_2)2d \tag{1}$$

where λ is the wavelength of light and d is the thickness of the grating. Reflection from the grating results in a diffraction pattern in far field. To calculate the best aspect ratio to achieve the maximum efficiency, a computer simulation was performed. Figure 2 shows the intensity of the 0th order of diffraction for different aspect ratio and different

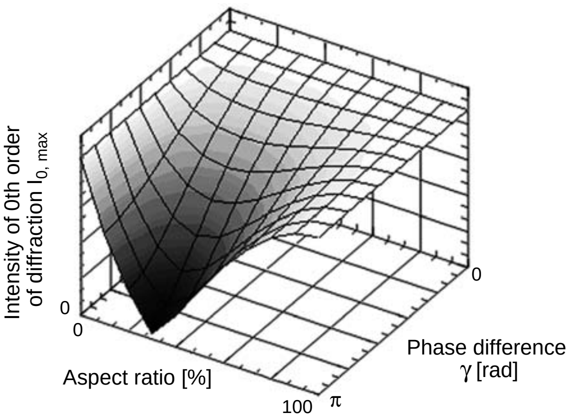

Fig. 2. Diagram of the intensity of the 0th order of diffraction in different aspect ratio and phase differences.

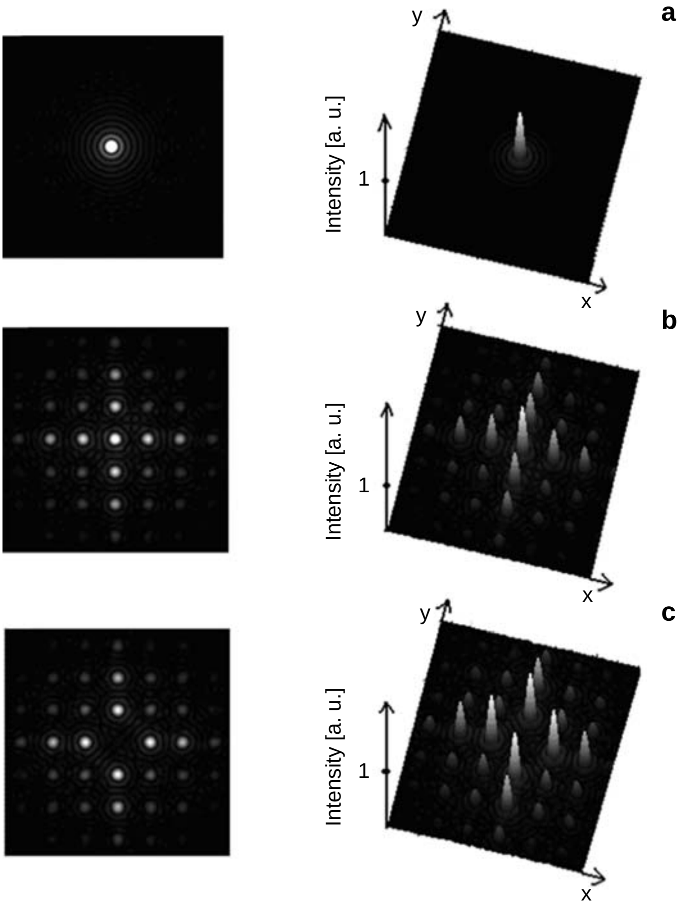

Fig. 3. Diffraction pattern of a 2D grating, when aspect ratio is 29.3% for $\gamma = 0$ (**a**), $\gamma = \pi/2$ (**b**), $\gamma = \pi$ (**c**).

phase differences. As seen in the figure, at $\gamma = \pi$ and AR = 29.3%, the intensity of the 0th order of diffraction becomes zero. In this case, the incoming light diffracts to the 1st and higher diffraction orders. Figure 3 shows the diffraction pattern for $\gamma = 0$, $\pi/2$, π, when AR = 29.3%.

Now suppose that the holes of a 2D grating are filled with a liquid whose refractive index is dependent on temperature. By changing the temperature, the refractive index is changed and using Eq. (1) the phase difference γ is changed. If $\alpha = (\mathrm{d}n/\mathrm{d}T)$ shows the dependence of the refractive index of the liquid on temperature, then parameter n_2 in Eq. (1) can be replaced by $\alpha\Delta T$, where ΔT is the amount of change in the temperature. In our experiment, we used nitrobenzene as a liquid with high temperature-dependent refractive index. For nitrobenzene we have $\alpha = -4.7\times10^{-4}$ K^{-1} [8].

3. Experimental results

A conventional lithography technique was used to fabricate the thermally tunable reflective grating (TTRG). First, a layer of photoresist was spin coated on a glass substrate. A 2D grating with a 100-μm period was then patterned on photoresist material. Next, the grating structure was etched into the glass substrate using a 35% HF solution. Different gratings with depths equal to 1.47, 4.45, 5.5 and 8.3 μm were fabricated by controlling the etching time. The etching depth of the glass was measured by a surface profile meter system. The holes of the grating were filled with nitrobenzene and a 300-μm thick double side polished silicon wafer was put on it, as shown in Fig. 4. The silicon wafer plays the role of a reflector at 532 nm (40% of reflection) and also as an optical window at $\lambda = 10.6$ μm.

3.1. Dependence of the intensity of the 1st order of diffraction on temperature

To study the intensity of the 1st order of diffraction depending on temperature, a setup as shown in Fig. 5 was used. In this setup, the TTRG was placed in a pot which was filled with nitrobenzene and the pot was put on a hotplate/stirrer. A 532 nm laser was split by a beam splitter (BS) and directed to the TTRG. After reflection, the laser beam

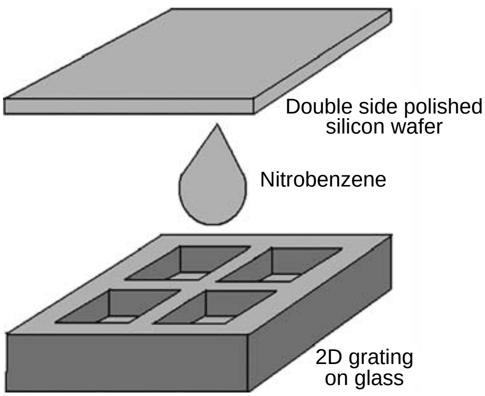

Fig. 4. Schematic of the 2D reflective grating.

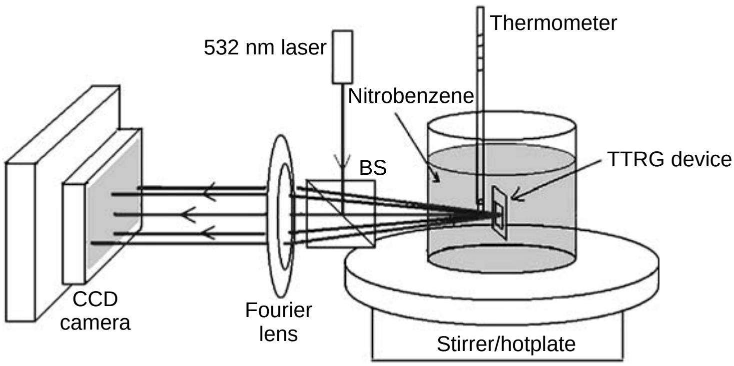

Fig. 5. Experimental setup for measuring the dependence of the intensity of the 1st order of diffraction on temperature.

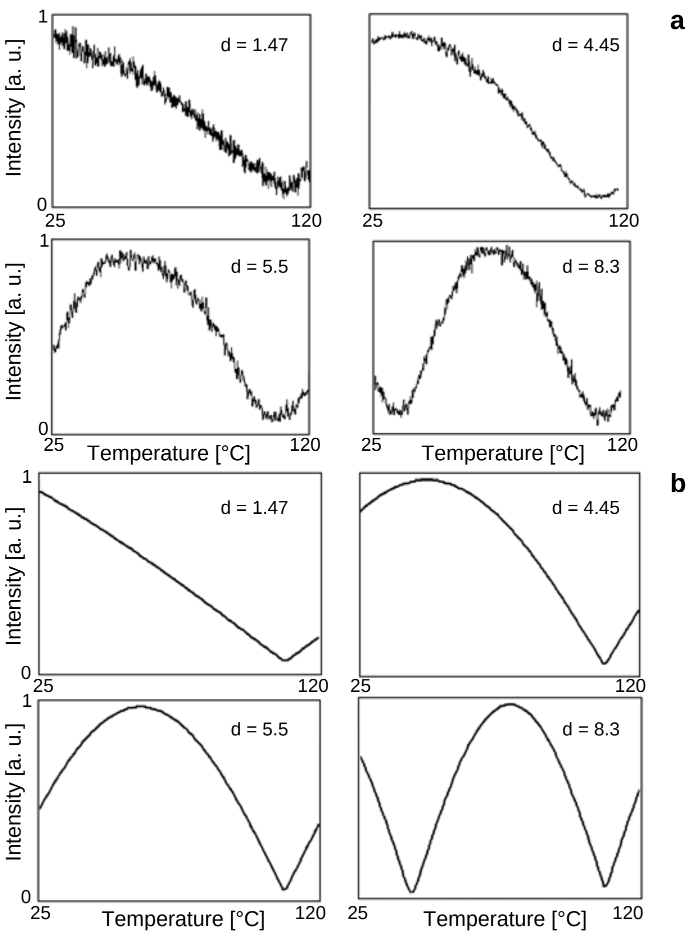

Fig. 6. Intensity of the first order of diffraction versus temperature for gratings with different depths. Experimental results (**a**) and computer simulation (**b**).

is passed through a Fourier lens and produces a diffraction pattern on a CCD camera. During the experiment the hotplate heats the solution and diffraction pattern is captured at different temperatures. Figure 6**a** shows a diagram of the intensity of the 1st order of diffraction versus temperature for different grating depths. As seen in this figure, as the depth of the grating increases, the number of cycles in the intensity of the 1st order of diffraction is increased. To compare these results with theory, numerical calculations for the intensity of the 1st order of diffraction versus temperature were performed, the results of which are shown in Fig. 6**b**. In these diagrams we assume that the grating is made of glass with $n_1 = 1.52$ and the refractive index of nitrobenzene is assumed to be $n_2 = 1.56$ at $T = 25$ °C for $\lambda = 532$ nm. As seen in these figures, the intensity of the 1st order of diffraction of all gratings, approach zero at about 110 °C. In this temperature the refractive indices of nitrobenzene and glass become equal.

3.2. Measurement of a CO_2 laser beam profile

To measure the beam profile of a CO_2 laser, a setup as shown in Fig. 7 was used. In this setup, a CO_2 laser beam incident on the TTRG from the silicon side is absorbed

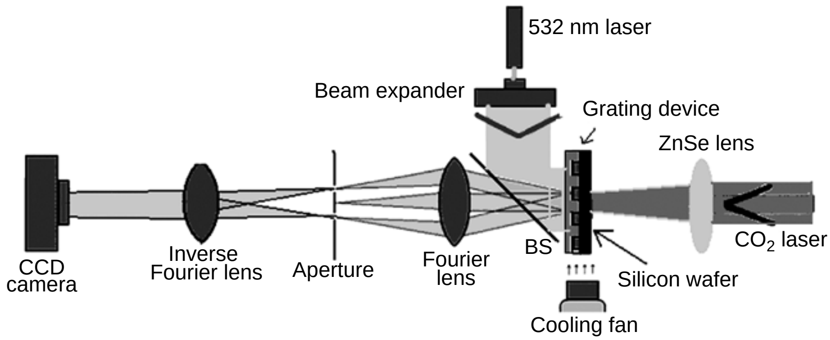

Fig. 7. Schematic setup for measuring CO_2 laser beam profile.

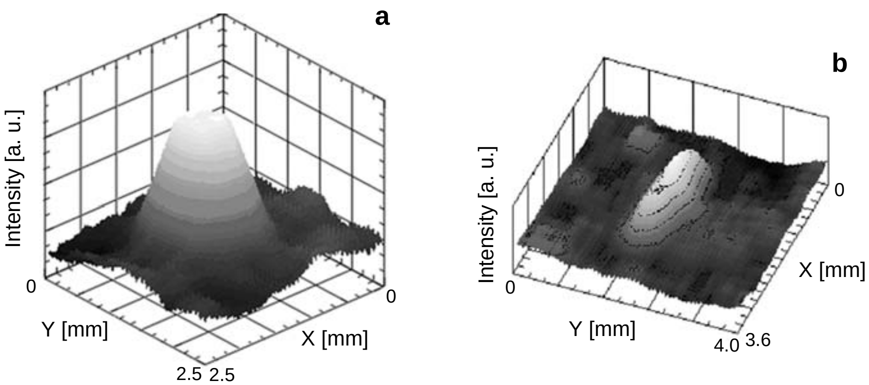

Fig. 8. Measured CO_2 laser beam profile when the ZnSe lens is perpendicular to the CO_2 laser beam (**a**) and when the ZnSe lens is tilted about 45° (**b**).

in the grating structure and warms it up. A 532 nm laser is expanded and irradiates the grating, from the glass side. After passing through the grating, the visible light reflects back from the silicon slab and is directed to a $4f$ imaging system. A high pass spatial filter is used to keep the first order of diffraction for imaging. A ZnSe lens (for its transparency to 10.6 μm) with a 10 cm focal length, is placed in front of the grating. By tilting this lens, the beam profile of the CO_2 laser is changed.

A grating with a 1.47-μm depth was used for this experiment. The images captured were analyzed to plot a 3D diagram of a 0.2 watt CO_2 laser beam profile. Figure 8 shows the beam profile of CO_2 laser when the ZnSe lens is perpendicular and in 45° position to the CO_2 laser beam.

3.3. Measuring the response time of the system

Some silicon devices have already been fabricated with very good response times [9].

In another experiment, the response time of the TTRG was measured. The same setup as in Fig. 7 was used, except that a chopper was placed in front of the CO_2 laser and a fast photodetector was used instead of the CCD camera. By chopping the CO_2 laser beam, the signal of the photodetector was monitored by an oscilloscope. Figure 9

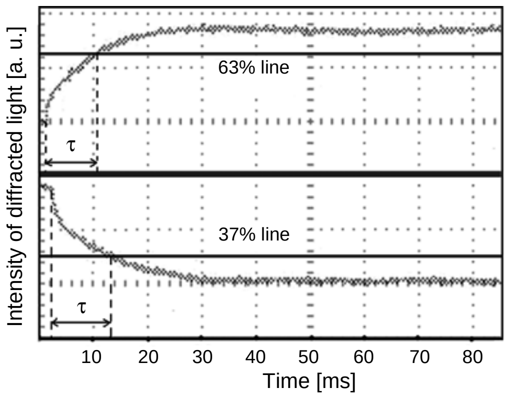

Fig. 9. Detected signals from photodiode when CO_2 laser is chopped on (upper diagram) and off (lower diagram). The response time of the system is shown by τ parameter.

shows the measured signals. As seen in this figure, the response time of the TTRG, the time in which the signal exceeds 63% of its entire changes, is about 10 millisecond which is fast enough to be used for imaging applications.

4. Summary and conclusions

In this article, fabrication and application of a 2D tunable reflective grating was discussed. Some simulations were done to characterize such grating. Gratings with different depths were fabricated and etched into a glass substrate by conventional lithography technique. The holes of the grating were filled with nitrobenzene, the refractive index of which highly depends on temperature. A silicon wafer was placed on the grating as a transparent window for the CO_2 laser beam. A relation between the temperature and the intensity of the first order of diffraction at the wavelength of 532 nm was investigated at first. A CO_2 laser beam was irradiated on the grating, warmed it and made a temperature profile the same as that of a CO_2 beam profile. In a $4f$ imaging system the intensity of the 1st order of diffraction was used to image the grating on a CCD camera. The images captured were analyzed to extract the beam profile of CO_2 laser.

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