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A 50kHz Micromachined Electrostatic Driven Vibratory Grating Laser Scanner

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Abstract

A 50kHz micromachined electrostatic driven vibratory grating laser scanner has been successfully developed for high-speed laser scanning applications. Unlike the conventional grating platform having uniform thickness across the entire diffraction surface, the grating platform in this study is thinned and reinforced by a circular frame, which is used to reduce its rotational inertia and keep its rigidity. The scanner is fabricated using a simple silicon-on-insulator (SOI) technology based micromachining process with only 4 photo masks used. This paper presents the design, simulation, fabrication process and experimental measurement results of the high-speed vibratory grating scanner. The prototype scanner with a 1mm diameter diffraction grating is capable of scanning at 50.192kHz with and optical scan angle of 14.1º when illuminated with a 635nm wavelength incident laser beam.

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1. Introduction

High speed laser scanning technology has been required and utilized in a wide variety of applications, such as raster scanning displays [1]-[4], barcode scanners [5], laser printers [6] and confocal microscopy [7]. The micro-electromechanical-system (MEMS) technology based miniaturized laser scanners were mostly developed in recent years, especially micromirror laser scanners [8]-[9]. Micromirror laser scanners utilize the deflection of a micromachined thin reflector to scan the laser beam rather than a macro reflector. This results in significant amount of outstanding advantages, such as a miniaturized device size, a high scanning speed, low power consumption and low per-unit cost. However, the rigidity of a micro mirror is normally incomparable to a macro mirror, due to the nature of the micromachining process. The dynamic deformation of the micro mirror under out-of-plane excitations

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will introduce significant aberrations to the optical system [10]-[11], especially for high-speed scanning applications. MEMS vibratory grating scanners [12]-[18], which utilize the in-plane rotation of a diffraction grating to scan the laser beam, are developed for high-speed scanning applications. Since the diffraction grating platform rotates in-plane, the non-rigid-body out-of-plane deformation during the operation can be ignored. Thus the MEMS vibratory grating scanners have the potential to scan at high scanning frequency with little dynamic aberrations.
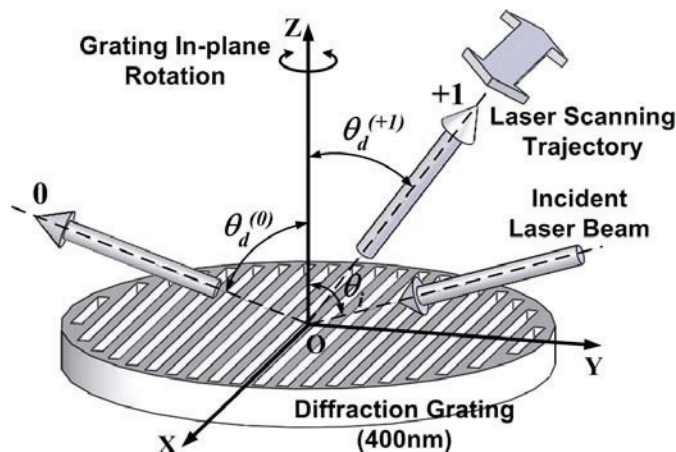

Fig. 1. Working principle of a MEMS vibratory grating scanner.

Fig. 1 shows the working principle of a MEMS vibratory grating scanner. The diffraction grating lies in the XOY plane and the grating grooves orientated along X axis. The incident laser beam lies in the YOZ plane and illuminates on the diffraction grating with a proper incident angle. When the diffraction grating rotates along Z axis, the diffracted laser beam (except 0th order diffraction beam) will scan accordingly.

The scanning speed of a micromachined vibratory grating scanner is proportional to the total stiffness of suspension flexural beams and inversely proportional to the rotary inertia of the grating platform. To increase the scanning speed, we can either increase the total stiffness of suspension flexural beams or reduce the rotary inertia of the grating platform. Since the maximum allowable deformation of the flexural suspension beams, which is determined by their internal stress, limits the scanning amplitude, the stiffness of a single flexural beam cannot be infinitely increased. Because excessive stress will be introduced, which is possible to cause the brittle fracture of the flexural beam, which will significantly reduce the scanner's scanning amplitude. Thus multiple flexural beams configuration should be adopted to increase the total stiffness of flexural beams without introducing excessive stress. Besides, reducing the rotary inertia of the grating platform is an effective way to reduce the total stiffness so that the stress inside each flexural beam is minimized to achieve high scanning speed with large scanning amplitude.

In this study, the grating platform was thinned by deep-reactive-ion-etching (DRIE) process from its backside and reinforced by a circular frame, which is used to keep the rigidity of the grating platform. The total rotary inertia reduction is around 42.4%. Besides, the internal stress of a single flexure is further reduced by multiple-beams suspension configuration. The prototype scanner with a 1mm diameter diffraction grating is capable of scanning at 50.192 kHz with an optical scan angle of 14.1º. The design, simulation, fabrication process and measurement results of the high-speed vibratory grating scanner are presented.

2. Scanner design and simulation

The schematic illustration of the high-speed vibratory grating scanner is shown in Fig. 2 (a). The diffraction grating with a period of 400nm is patterned on a round grating platform with a diameter of 1mm and a thickness of 80μm. As shown in Fig. 2 (b), the grating platform was thinned from its backside by a round cavity to reduce its rotary inertia. The rigidity of the grating platform is ensured by a circular reinforcement frame at its edge. The designed diameter and the depth of the round cavity are 850μm and 65μm respectively. This results in a 42.4%

reduction of its rotary inertia, so that the total stiffness can also have a reduction of 42.4% without changing the scanning speed.
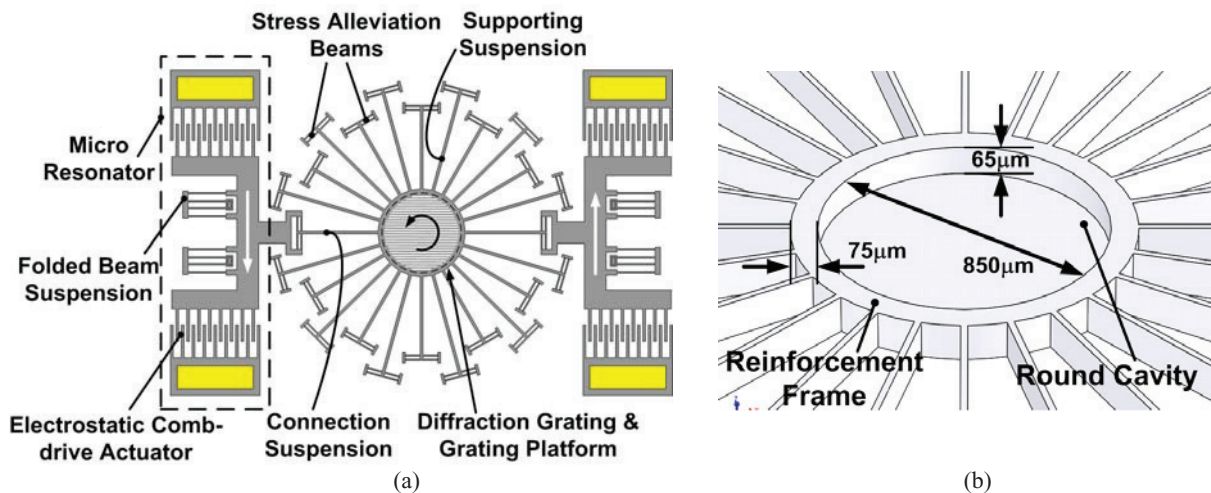

Fig. 2. Schematic illustration of the micromachined high-speed vibratory grating laser scanner showing (a) the top view of the whole device; (b) the bottom view of the grating platform.

The grating platform is connected to the substrate through 20 supporting flexural beams. Among these beams, 12 of them, which are designed to be longer than others to save space, have a beam length of 1300μm, width of 30μm and thickness of 80μm. The other 8 of them have a beam length of 1050μm, width of 27μm and thickness of 80μm. Two sets of electrostatic comb-driven micro resonators are configured symmetrically and each of them is attached to the grating platform through one connection flexural beam with beam length of 1050 μm, width of 27 μm and thickness of 80 μm. Each of the supporting flexural beams and connection beams has 2 pairs of perpendicularly connected stress alleviation beams having a beam length of 255μm, width of 6μm and thickness of 80μm, which are used to reduce its axial stress during the operation hence reducing the nonlinearity of the laser scanner. The electrostatic comb-driven micro resonator is suspended by 96 sets of folded beam suspensions with beams of length 170 μm, width 8 μm and thickness 80 μm. Each comb-drive resonator has a total number of 164 movable fingers on one side with finger length of 64 μm, width of 7 μm, thickness of 80 μm, finger gap of 4 μm and initial finger overlap of 30 μm.

While operating, the two comb-driven micro resonators are driven at the same frequency and vibration amplitude but 180 degrees out-of-phase with each other. The translational vibrations of the comb-drive resonators couple through the suspension flexures to the grating platform producing an in-plane rotational vibration around its geometric center, which in turn causes a diffracted laser beam from the grating to scan.

From the view of the mechanical engineering, the scanner can be treated as a 2-DOF spring-mass vibration system. Finite element (FE) simulations using the commercial software package ABAQUS^{TM} (type of analysis: natural frequency extraction, element type: C3D8R, number of elements: 294850, number of DOF: 6) was conducted to predict the dynamic performance of the scanner, such as resonant frequencies and mode shapes. The mode shape can be defined as the ratio of the rotational angle of the grating platform and the lateral displacement of the micro resonator. Due to the limitation of the computation power and elaborate features in the actual device, it is necessary to make some simplifications to the FE model. In our model, each micro resonator was simplified to an equivalent mass (rigid plate) supported by four flexure beams having the same total spring constant as that of the original 96 sets of folded-beam suspensions. The grating platform, flexure beams connecting the resonators to the platform and their associated stress alleviation springs were modeled according to the original design. Although there are two resonating modes are expected for a 2-DOF vibration system. The high-speed MEMS grating scanner is preferred to work at its first resonating mode. The reason is that the first resonating mode has higher mode ratio resulting in larger scanning amplitude, less risk of brittle fracture of the connection flexural beams, compared with

the second resonant mode. The FE simulation result showing the preferred working mode and the resonant frequency are shown in Fig. 3. In the working mode, the diffraction grating platform rotates in the same direction as the couple formed by the two comb drive resonators. The corresponding resonant frequency is 56913 Hz and mode ratio is 7.483deg./µm
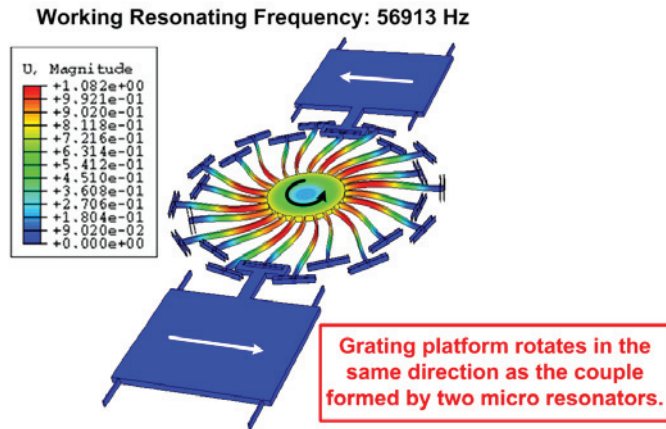

Fig. 3. FE simulation results showing the preferred working mode and its resonant frequency.

3. Fabrication process

Silicon-On-Insulator (SOI) micromachining technology was used to fabricate the prototype device and four photo masks were used. The fabrication process flow is illustrated in Fig. 4. The SOI wafer used has an 80 µm thick heavily doped silicon device layer, 2µm thick buried oxide (BOX) layer and a 650±25 µm thick silicon substrate.
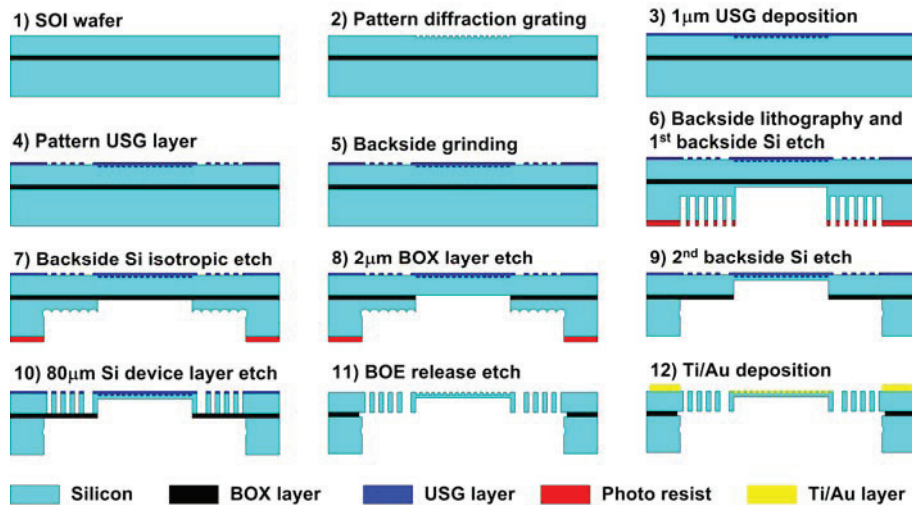

Fig. 4. Fabrication process flow of the prototype high-speed vibratory grating scanner.

As shown in the above schematic illustration, the binary diffraction grating with 400nm grating pitch and 50% duty cycle was firstly patterned using deep-UV lithography and timed plasma etching. The groove depth of the diffraction grating was around 150nm so that the optimal diffraction efficiency can be achieved. Then, 1µm undoped silicon glass (USG) layer was deposited on the top of the wafer and patterned using Reactive Ion Etching (RIE) process. The hard mask layer of the grating platform, suspension beams and electrostatic comb-drive actuators

was defined in this step for the future process. Next, the backside of the SOI wafer was grinded and polished until the thickness of the silicon substrate is around 500µm. After that, the SOI wafer was patterned on the backside using a specially designed mask for the future delay etching. The etching region was partitioned to different sections with different trench width by a set of concentric circular dummy fin structures. The region of the round cavity of the grating platform has the biggest trench width resulting in highest etching rate. The SOI wafer was then etched from its backside by the 1st DRIE process until a few microns of silicon are left in the region of the round cavity. The thickness of the remaining silicon in the etching region was less than 45µm. Next, a plasma recess etching process removed all the dummy fin structures and exposed the BOX layer in the round cavity region. The 2µm BOX layer was then etched through by the subsequent RIE process, which stopped at the silicon device layer. Next, the round cavity region and the rest were etched simultaneously by the 2nd DRIE process. The etching process stopped when the depth of the round cavity is around 65µm. All the BOX layer of the rest of the etching region was exposed and etched in the following RIE process. Subsequently, the 80µm thick silicon device layer was etched by another DRIE process to form the grating platform, suspension beams and comb-drive actuators. All structures were then released from backside using BOE solution (buffered oxide etchant solution with 6 parts of 40% NH_4F and 1 part of 49% HF). After that, a 1000 Å/5000 Å thick Ti/Au layer, which is used as the metal pad for wire bonding, were evaporated on the top of the wafer through a shadow mask. Finally, a 100 Å/800 Å Ti/Au layer was evaporated on the wafer's top surface to enhance the reflectivity of the diffraction grating.

The SEM image showing the top and bottom view of the fabricated prototype scanner are shown in Figs. 5(a) & (b) respectively. The geometry dimension of the round cavity at the back of the grating platform was measured using a white light interferometer. The diameter and the depth of the round cavity are measured to be 842µm and 64.85µm, which agree well with design parameters indicating the feasibility and the reliability of the fabrication process.
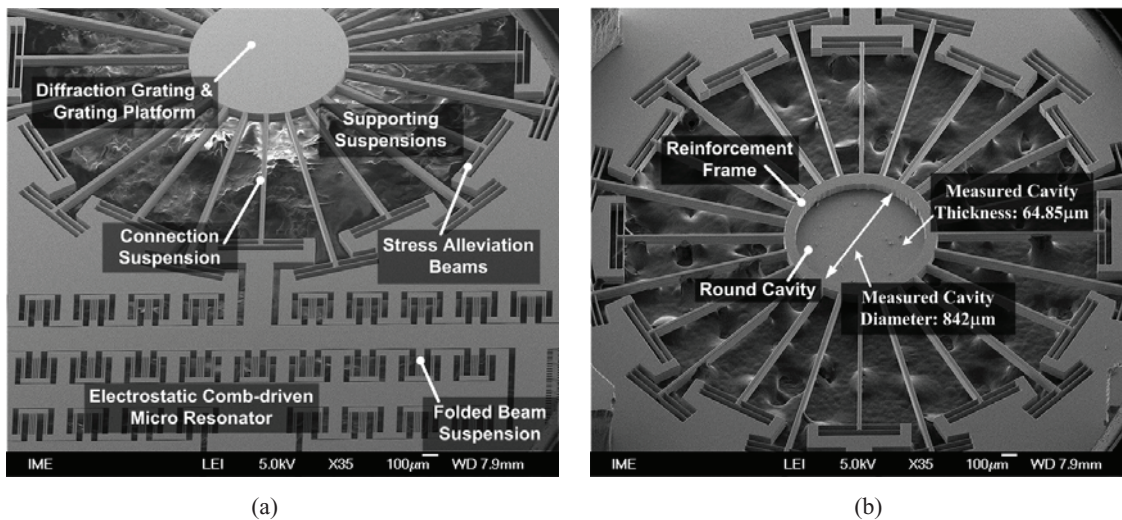

Fig. 5. SEM images showing the (a) top view and (b) bottom view of the fabricated prototype device.

4. Experimental results

The prototype high-speed vibratory grating scanner was tested using a linearly polarized laser beam with a wavelength of 635nm from a 5mW laser diode module. Since the grating pitch is 400nm, the incident angle of the illuminated laser beam was determined to be 73.3º so that the bow-free scanning conditions [14] are fulfilled. The prototype high-speed MEMS grating scanner was mounted in a vacuum chamber with a vacuum pressure of 0.12mTorr, which is to raise the quality factor. Each electrostatic comb-drive resonator was driven by a push-pull mechanism with a DC bias and an AC sinusoidal signal. A projection screen and a beam dump were aligned perpendicular to the 1st and 0th order diffracted beams respectively when the diffraction grating remained motionless.

After applied voltages to the driving actuators, the grating platform vibrates resonantly and the 1st order diffraction beam scans accordingly while the 0th order beam remains stationary. The scanning trajectory of the 1st order diffraction beam was projected on the projection screen and the 0th order diffraction beam was dumped. The optical scan angle was determined by measuring the length of the projected laser trajectory and the distance between the screen and the device. The frequency response of the prototype high-speed MEMS grating scanner was obtained through sweeping the frequencies of the driving AC sinusoidal signal.
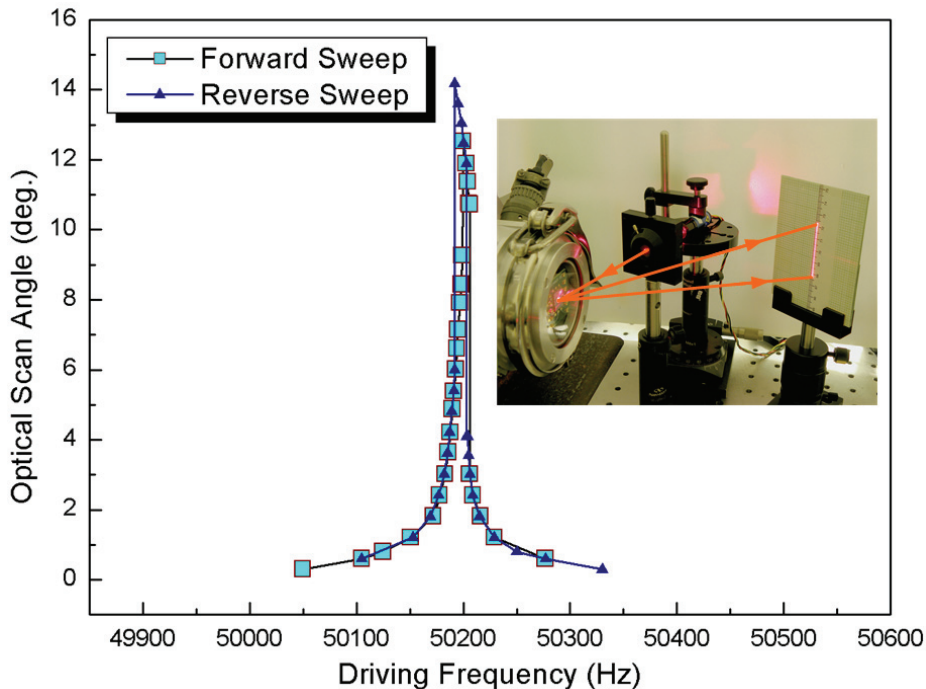

Fig. 6. Measured frequency response of the preferred working mode as well of the photograph of the laser scanning trajectory.

The frequency response of the prototype high-speed MEMS grating scanner near the region of the first resonating mode was then measured with driving voltages of 100V dc bias and 200V ac peak-to-peak voltages. Fig. 6 shows the measured frequencies of the working mode as well as the photograph of the laser scanning trajectory. The prototype scanner was capable of scanning at a frequency of 50.192kHz with an optical scan angle of 14.1º. Compared with our previous work [16], the performance of the scanner in this study is significantly improved, where the scanning amplitude is 280% increased with the scanning speed drop of only 10%.

5. Conclusions

We have presented the design, simulation, fabrication process and measurement results of a 50kHz micromachined electrostatic vibratory grating laser scanner. To further increase the scanning frequency without reducing the scanning amplitude, the grating platform is thinned from its backside through a round cavity to reduce its rotary inertia and a circular reinforcement frame left at the edge of the grating platform, which is used to keep its rigidity during the scanning. The total rotary inertia reduction is around 42.4%. Besides, multiple-beams suspension configuration is adopted to further reduce the internal stress of a single flexure. A prototype high-speed vibratory grating scanner were successfully fabricated using SOI technology based micromachining process with only 4 photo masks used. The prototype scanner with a 1mm diameter diffraction grating is capable of scanning at 50.192kHz with and optical scan angle of 14.1º when illuminated with a 635nm wavelength incident laser beam.

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