Finite Element Analysis in the Development of the MEMS-based Compound Grating (MCG)

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ABSTRACT

This paper presents the development of the 1 μm ruled MEMS-based Compound Grating (MCG) in which the structural material of the rulings is SiO_2 coated with Cr/Au as the top electrode. The MEMS simulation package IntelliSuite™ is used to determine the structural dimensions and to study the electrical actuation property. Four different versions of MCGs are studied. The lengths of the rulings vary from 100 μm to 150 μm. Using Finite Element Analysis, the structural integrity is examined and the electrical actuation properties are predicted. Finally, the device prototypes are successfully fabricated and initial experimental results are compared with the simulation results.

Keywords: MEMS, modeling and simulation, Finite Element Method, micrograting, diffraction grating

1 INTRODUCTION

In the development of any Micro-Electro-Mechanical Systems (MEMS) device, many design considerations are involved including fabrication capability and structural integrity which govern the layout and design. To determine the optimal design, the trial-and-error method is costly and time consuming. However, the use of computer modeling and numerical simulation can dramatically reduce the device development cycles. This concept is applied to the development of the MEMS-based Compound Grating (MCG) [1] in this paper. The micro grating is a basic building component for many micro-optical systems and is very attractive for applications in free-space optical interconnects, optical modulation [2], etc, where the reconfigurable micrograting can provide more flexibility. The MCG presented in this paper is a microstructure with rulings movable in vertical direction by electrostatic force. Such an MCG can be used as the heart of a flexible, adjustable grating for compact spectrometers [3]. With more conventional technology, these spectrometers would require multiple gratings and a mechanical method to insert and remove them from the optical path.

Regarding the optical performance, gratings with small grating constants are generally desired. Using the standard MUMPs run (Cronos Integrated Microsystems, Inc.), several versions of MCG have been fabricated and tested [1, 3]. However, the grating constant is limited to no less than 4 μm since it is a general-purpose process. To investigate the optical performance and study the electromechanical behavior of MCGs with smaller grating constant, a customized process flow is being developed to fabricate the 1 μm ruled MCGs (grating constant of 2μm). As can be appreciated, the required structural integrity limits the aspect ratio (length/width) of the ruling, therefore a compromise results. Moreover, the actuation voltage for the electrostatic operation of the device is another aspect to be considered. In order to fix any design flaw before the device fabrication, a MEMS simulation package IntelliSuite™ [4] is used to assist in the structural design. This paper first briefly introduces the customized MCG structure. Then, the structural dimensions are optimized with the help of Finite Element Analysis. The structural integrity and the electrical actuation property are studied extensively in Section 3. Finally, the initial experimental results are compared with the simulation results.

2 CUSTOMIZED MCG STRUCTRURE

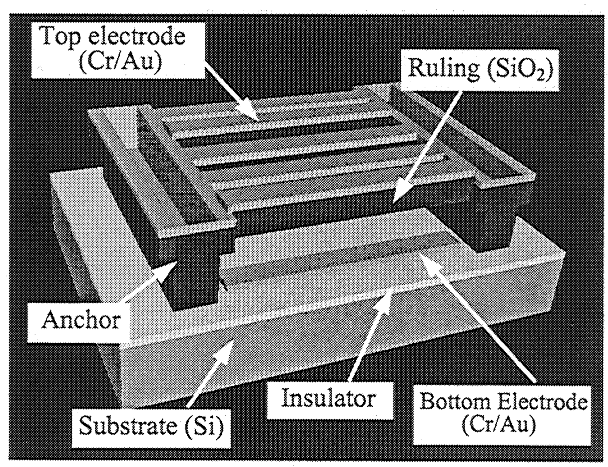


Fig. 1: The schematic of the customized MCG.

A schematic view of the customized MCG is shown in Fig. 1. Individual electrode structures (individual pairs, trios or quartets, etc.) are placed below the rulings. Fig. 1 is an example of trios. Cr/Au is used as the bottom electrode. SiO_2 is used as the ruling structural material and Cr/Au again as the top electrode of the rulings. This Au coating provides a means to apply voltage between it and the bottom electrodes so that the rulings could be pulled down to reconfigure the optical surface. In addition, the high reflectivity of Au enhances the optical signal from the top rulings. In this structure, the rulings with bottom electrodes underneath are higher than the rulings without bottom electrodes. With the application of voltage between rulings and the bottom electrodes, ruling positions change, therefore, a new diffraction surface results and the diffraction patterns change accordingly. As long as the net change of height difference reaches ¼ of the wavelength, the diffraction order switch will happen [1].

Different from MCGs made by the MUMPs runs, we choose to use SiO_2 as the structural material because of its smaller Young's modulus compared to polysilicon, and 1 μm ruled structure to decrease the grating constant. A simulation study is necessary to help optimize the device design and predict the device performance.

3 NUMERICAL SIMULATION

3.1 Simulation Strategy

MEMS simulation requires numerically solving the partial differential equations (PDE) describing the complicated interaction between different energy and signal domains. There exist many numerical solvers for PDEs, such as finite differences, finite element (FE) solver and boundary element (BE) solver. However, only FE solver and BE solver are suitable for arbitrary complex geometries and linear, nonlinear and time-varying PDEs [5].

For MCGs, the structural integrity is examined by the Mechanical Analysis (MA) in which the ruling deformation is caused by the material residual stress only. The electrical behavior under selected voltages is examined by the ElectroMechanical Analysis (EMA) in which the deformation is caused by the combination of applied voltage and residual stress. Both FE solver and BE solver are used by the IntelliSuite^{TM}. The ElectroStatic Analysis module uses only the BE solver. The MA module uses the FE solver. The EMA module iterates between the FE and BE solvers. The FE algorithm first calculates any stresses and deformations resulting from non-electrostatic forces. The resulting (deformed) geometry is then used in the BE solver to calculate the electrostatic results. The electrostatic pressures measured from the BE solver are then put back into the FE solver. These pressures can further deform the structure. The updated structural information is then put back into the BE solver. This process repeats itself until the solution converges.

3.2 Simulation Model

There are a couple of ways to create a numerical calculation model. One way is to start from the 2D mask layouts. A 3D solid model is automatically generated using a fabrication file that describes the geometrical effects of the MEMS processing steps. The surfaces of the model are then automatically identified and discretized resulting in the initial meshes [4,5]. This method is a good demonstration of the automation capability of the MEMS simulation package but the model is not an optimized one for the numerical simulation. Further, it can't be applied to some complicated structures like the MCG. The better way of constructing the numerical model is by a 3D interactive builder, in which the mesh can be optimized manually and locally.

An MCG structure includes thousands of rulings and electrodes. To significantly cut down the computer calculation time, only three bottom electrodes and the relevant rulings are built into the numerical model and they are sufficient to represent the concerned properties of an MCG. A part of the numerical model is demonstrated in Fig. 2. This is an MCG with electrodes underneath every other ruling. Rulings with electrodes underneath are called Elevated Rulings (ER) and those without electrodes are called Plain Rulings (PR). Fig. 2 also clearly shows the numerical meshes which are only the constructed coarse ones. They are refined according to the structural dimension when analysis is performed.

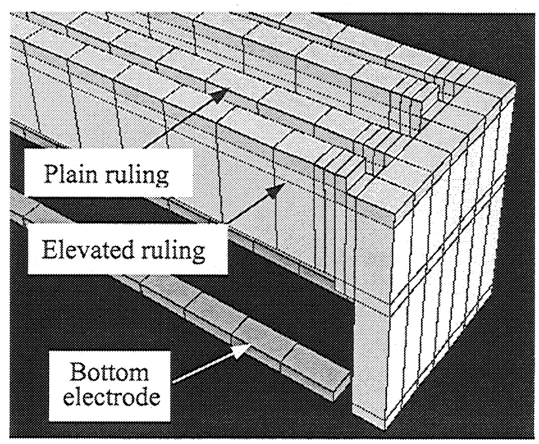


Fig. 2: MCG model in the numerical simulation.

3.3 MCG Configuration

Using the MUMPs MCG dimension as the reference, the customized MCG structure is constructed and the dimensions are shown in Table 1 (marked by MCG0). The MA is conducted first to investigate the structural integrity. In MCG0, the 1μm wide ruling has a very large aspect ratio of 220. With SiO_2 bearing compressive stress and Au bearing tensile stress, the structure buckles and no meaningful simulation result is obtained.

The 3 μm ruled MCG in MCG0 has appropriate structural integrity. Then, the EMA is used to examine the electrical behavior. Unfortunately, the result shows that it needs more than 60V to pull down the raised rulings and make the optical order switch, which is impractical in MEMS applications, whereas the MUMPs MCG needs about 27 V [6]. This is because the ruling material, SiO_2, decreases the electrostatic force compared with the similar space structure but with rulings made by doped polysilicon in the MUMPs run.

To enhance the structural integrity, the rulings have to be shortened. To lower the actuation voltage, the space and ruling thickness have to be decreased. The minimum space is determined by the fabrication technology. A spacing of

1.5μm is necessary for complete sacrificial layer etch. A thicker ruling has a better structural integrity but decreases the electrostatic force. A nominal value of 1μm is studied in the simulation. To investigate the performance of different schemes, various dimension MCGs (as shown in Table 1, MCG1---MCG4) are constructed. Here, the 3 μm ruled MCG4 is used as the reference.

MCGs	RW (μm)	RL (μm)	Space (μm)	RT (μm)	ET (μm)	R:E
MUMPs	3	220	2.75	1.5		3:1
MCG0	1 ,3	220	2.5	1.5	0.15	3:1
MCG1	1	100	1.5	1	0.15	3:1
MCG2	1	120	1.5	1	0.15	2:1
MCG3	1	150	1.5	1	0.15	3:1
MCG4	3	150	1.5	1	0.15	2:1

Table 1: Nominal values of MCG dimensions. (RL: ruling length; RW: ruling width; Space: space between the lower side of ruling and the top side of bottom electrode; RT: ruling thickness; ET: electrode thickness; R:E: ratio of ruling to electrode. As always, the interval between rulings is the same value as the ruling width.)

3.4 Results and Discussions

MCGs	Ruling type	Deform. of MA (μm)	Displacement of EMA (μm)	Net change (μm)	Volt. (V)
MCG1	ER	0.050	0.0189	0.002	40
	PR	0.013	-0.017		
MCG2	ER	0.082	-0.051	0.077	40
	PR	0.024	-0.186		
MCG3	ER	0.281	0.171	0.241	20
	PR	0.135	-0.216		
MCG4	ER	0.312	0.055 (-0.173)	0.148	25
	PR	0.152	0.043 (-0.025)	(0.308)	(30)

Table 2: Vertical deformation of MCGs. (Positive value means bending up, negative value means bending down relative to the initial position.)

Table 2 shows the vertical deformation of the modeled ruling under both analyses. Regarding the MA results, with Cr/Au bearing the tensile stress and SiO_2 the compressive stress, all four structures bend up, i.e. the ruling center is higher than the anchor area. Also, there is a deformation difference between the two kinds of rulings even though the deformation is caused by the material residual stress only. The deformation of ERs are more than twice larger than that of PRs. In comparing all the 1 μm ruled MCGs, the longer the rulings, the larger the deformation. This is clearly shown in Fig. 3.

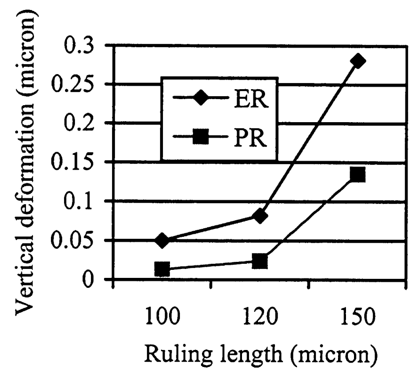
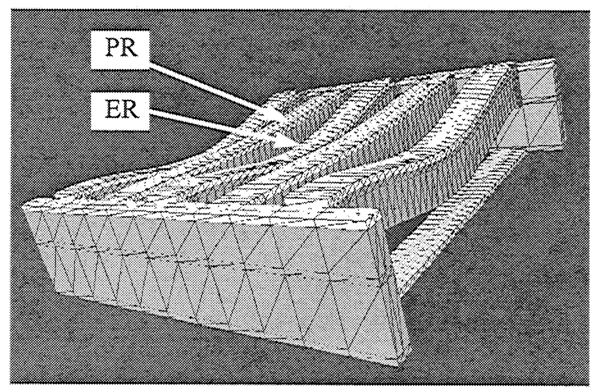
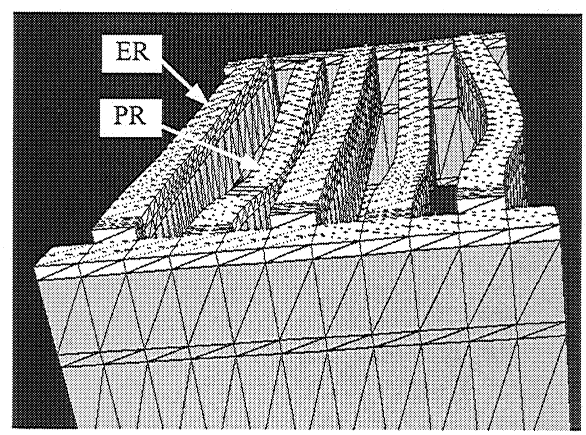


Fig. 3: Vertical deformation of 1 μm ruled MCGs.

When a voltage is applied between the top electrodes and the bottom electrodes, all the rulings are pulled down but in different amounts. Fig. 4 shows the EMA results of MCG4 and MCG2. As indicated in Table 1, MCG4 is a 3 μm ruled structure with ruling length of 150 μm. MCG2 is a 1 μm ruled structure with ruling length of 120 μm.



(a) 3 μm ruled MCG4



(b) 1 μm ruled MCG2

Fig. 4: Vertical displacement of MCGs under electrostatic force, ruling width dimension is exaggerated.

One can see from Fig. 4(a) that the ERs are pulled down more than the PRs in MCG4 which possesses a dimension of 3 μm wide rulings with electrodes underneath every other ones. In this case, the electrostatic force effects the ERs right above them more than the PRs adjacent to them. But for the 1 μm ruled MCG2, from Fig. 4(b), one can see that the PRs are pulled down more than the ERs. There are two possibilities: (1) The influence of the fringe effect at the edge of the electrodes increases as the rulings become narrower. (2) The ERs bend up more than the PRs due to the residual stress, which weakens the electrostatic force caused by the voltage between them and the underneath electrodes.

In order to further understand the impact of the residual stresses on the ruling displacement with an applied electric field, an EMA with zero material residual stress is performed. In this case, all the rulings have no initial deformation and the ERs are closer to the electrodes than the PRs. The result shows that the ERs bend down more than the PRs at the same voltage. Therefore, the initial deformation caused by the residual stresses is responsible for the lower than expected displacement of ERs. Even though the PRs are lower than the ERs in this case, as long as the net change of the height difference reaches ¼ of the wavelength, 1 μm ruled MCGs should be able to perform the order switch.

The vertical deformation of all MCGs under different voltage ranges is shown in Table 2. One can see that MCG1 is very stiff because of the short ruling length. Other MCGs deform reasonably under certain voltages. If a HeNe laser (wavelength of 632.8 nm) is used as the light source, MCG4 should perform switch at voltage between 25 V and 30 V.

4 EXPERIMENTS

All the MCGs are fabricated using a customized process flow. Fig. 5 shows the released 1 μm ruling structure.

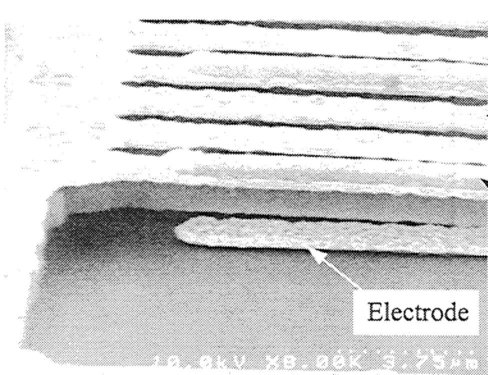


Fig. 5. SEM of the 1 μm ruled MCG.

An AFM is used to study the ruling deformation. Without voltage, all the rulings bend up, which is consistent with simulation results. For MCG3, the ERs deform about 0.200 μm more than the PRs, which is quite close to the 0.146 μm simulation result.

A sample of MCG4 was optically tested. A HeNe laser (λ=632.8 nm) was used as the incident light source. At 50V, the diffractive orders perform a distinct switch, which is higher than the simulation prediction. The explanation is that the material properties in the simulation are critical to the simulation results and they need to be extracted from the fabrication process. The values in the above analysis are from the general material database that might shift from the specific fabrication technology. Further, the simulation model is based on the nominal value of the dimension. The real dimension value is slightly different from the nominal value due to the fabrication variation. Therefore, the simulation models need to be refined to fit the real case.

5 CONCLUSIONS

The 1 μm and 3 μm ruled MCGs are studied using Finite Element Analysis to optimize the device design. The simulation results show that the rulings bend up due to the residual stress of the structural materials, resulting in a high pull-in voltage to achieve enough vertical displacement. These results explain the initial experimental result of higher than expected actuation voltage observed in the fabricated MCGs. A refined modeling effort is under way to improve the device design and predict the performance of MCGs.

ACKNOWDEGEMENTS

This project is sponsored by NASA under contract NAG5-7082. The authors greatly appreciate the help from Bruce Altemus for device fabrication, Gajendra Shekhawat and Rowald Haze for AFM measurement.

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