

Design of a MEMS Pitch Tunable Grating for Enhanced Scanning LiDAR

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Abstract:

This paper introduces a high-performance MEMS (micro-electro-mechanical systems) pitch tunable grating (PTG) as a LiDAR (light detection and ranging) sensor. While the challenges associated with its integration into self-driving cars are addressed, its potential application extends beyond this specific domain. Electrostatic-based comb actuators are employed to drive the device. To delay side pull-in instability attributed to this transduction mechanisms, an innovative flexural configuration is employed, extending the stable travel range up to 135 μm , resulting in a broad pitch tuning of 2.25 μm . The initial diffraction angles for the first two orders before actuation were $\pm 2.8^\circ$ and $\pm 5.5^\circ$; moreover, this remarkable pitch tuning resulted in a significant increase in the angle of the first and second orders, reaching 0.4° and 0.8° , respectively.

Keywords: MEMS, LiDAR, Optics, Sensor, Electrostatic

Introduction

The rising demand for automated driving due to its potential to prevent accidents, has led to a growing need for compact and affordable optical scanning systems. LiDAR stands out as a pivotal sensor for autonomous driving, offering the capacity to generate 3D data [1]. The currently dominant scanning solution in the automotive LiDAR market is bulky and has limitations related to duty cycle and inertia, leading to constraints on frame rate and increased power consumption. Consequently, MEMS-based LiDAR has gained considerable attention as a viable alternative, owing to its reduced size, low weight, and low power consumption. Thus far, two primary types of MEMS LiDARs have been investigated: mechanical and non-mechanical [2]. The first involves vibration-based sensing mechanisms utilizing resonant mirrors, whereas the latter utilizes light diffraction techniques, often implemented through solid-state gratings. Analyzing their advantages and drawbacks reveals why PTGs have garnered significant interest. They effectively bridge the gap between mechanical and solid-state LiDAR, providing an enhanced solution by widening the field of view (FoV) through pitch tuning between adjacent mirrors. This feature distinguishes them from solid-state gratings. While several papers have reported on PTGs driven by comb-drive actuators, to our knowledge, only one published research paper has investigated the potential use of MEMS-based PTGs in LiDAR

systems for autonomous vehicles [3]. However, this device faces significant challenges that must be overcome before it can serve as an alternative solution for available LiDAR sensors. These challenges include undersized dimensions (resulting in extremely low intensity of diffracted light), limited travel range (only 1.21 μm), low fill factor, and a resonant frequency exceeding 20 kHz, unnecessarily stiffening the device. The paper presents a MEMS-based PTG scanner to address these challenges.

Description of the System

Fig. 1 illustrates a 2D view of the proposed device, highlighting its main components. It consists of silicon-based central grating mirrors (120 in total, each sized $2000 \times 12 \mu\text{m}^2$) actuated by comb actuators, with two central anchors, all 80 μm thick. Guided beam springs, 150 μm in length and 4 μm in width, connect the grating mirrors, maintaining a 4 μm space between them. Additionally, eight tilted-folded flexures, with beams measuring 6 μm in width and 950 μm in length, are integrated. This suspension design enhances lateral stiffness while enabling large linear displacement in the actuation direction. The overall size of the mirror area meets the minimum requirement of MEMS mirrors for self-driving applications [2]. To comprehensively evaluate the device's performance, mechanical behavior is analyzed using COMSOL, followed by theoretical validation, while the optical characteristics are assessed through theoretical modelling.

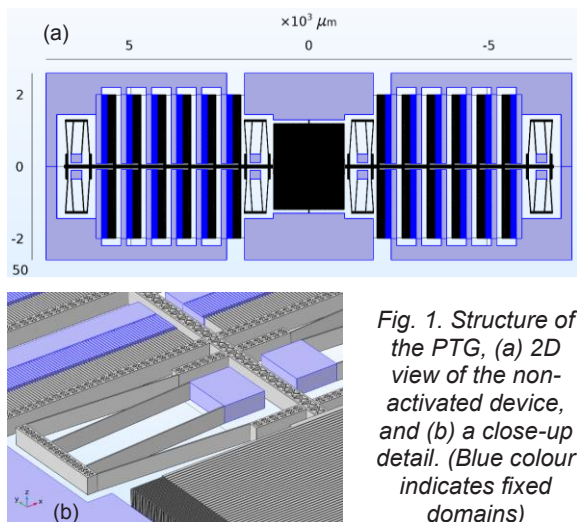


Fig. 1. Structure of the PTG, (a) 2D view of the non-activated device, and (b) a close-up detail. (Blue colour indicates fixed domains)

Discussion

The comparative analysis of the effective bearing ($K_{x, \text{eff}}$) and electrical (K_e) spring constants versus displacement, considering various suspension tilt values (d), is depicted in Fig. 2, obtained through analytic modeling. The results show that, depending on the tilt value, the bearing and electrical stiffness curves intersect at different points along the movement, indicating the maximum stable travel range. It is observed that a tilt value of $d=65 \mu\text{m}$ is optimal, offering the largest stable displacement of $135 \mu\text{m}$, significantly surpassing previous studies.

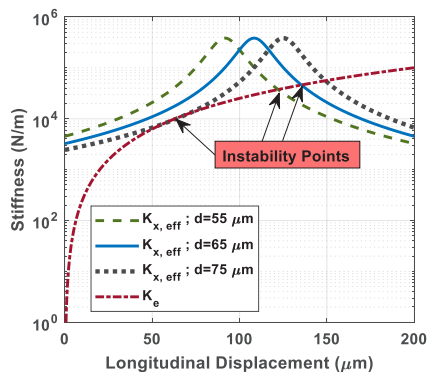


Fig. 2. Variation of stiffness with displacement

Figure 3a illustrates the voltage required to actuate the system when the gap between stationary and moving comb fingers is set at $4 \mu\text{m}$. This gap is deemed optimal due to design trade-offs: while a larger gap delays instability, it also substantially decreases the electrostatic force. The results obtained through theory and simulation are shown to be in good agreement. Due to this large stroke, the pitch is tuned by $2.25 \mu\text{m}$. Although, as expected, the duty cycle slightly decreases from 75% to 65% (albeit remaining high), the periodicity tuning extends to 14%, marking a significant improvement over previous findings [3]. The diffraction of incident light on the grating is described by Eq. (1):

$$\sin(\theta_m) + \sin(\theta) = m\lambda/(2P) \quad (1)$$

Where m , θ , λ , and P represent the diffraction order, incident light angle, incident light wavelength, and pitch. With the incident light wavelength set at 1550 nm , the initial diffraction angles for the 1st and 2nd orders of diffracted light, prior to actuation, is obtained $\pm 2.8^\circ$ and $\pm 5.5^\circ$, respectively. The relationship between the increase in diffraction angle and actuation voltage is illustrated in Fig. 3b, demonstrating a notably greater enhancement in diffraction angle compared to previously reported results.

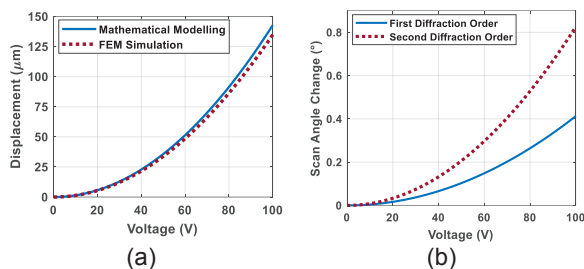


Fig. 3. Effect of actuation on: (a) displacement, (b) scan angle change

The natural frequency in PTGs is crucial for ensuring immunity to unwanted vibrations. According to [2], sensors used in cars must maintain a natural frequency above 800 Hz for reliable operation. An excessively high eigenfrequency leads to a stiff device, necessitating higher actuation voltage. Consequently, the device is designed to have a resonant frequency slightly over 800 Hz . Figure 4 shows the out-of-plane (1st mode) and in-plane (3rd mode) eigenfrequencies. This data confirms the device's complete resistance to unwanted vibrations. Moreover, the in-plane mode with a frequency of 894 Hz ensures high actuation speed, within the millisecond range.

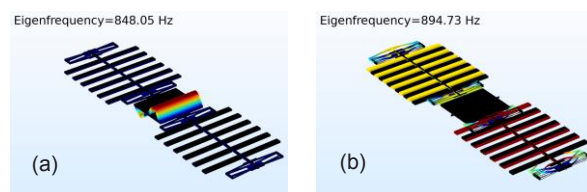


Fig. 4. Eigenfrequency modes: (a) first, (b) third

References

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