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MEMS MIRRORS FOR WEARABLE LIDAR

Richard Král, Tibor Vince

Technical University of Košice
Faculty of Electrical Engineering and Informatics
Park Komenského 3, 042 00 Košice
e-mail: richard.kral@tuke.sk, tibor.vince@tuke.sk

LUSTRA MEMS DLA PRZENOŚNYCH LIDAR

Streszczenie: *W artykule omówiono wybór i charakterystykę luster MEMS do systemów LiDAR noszonych na ciele, z naciskiem na efektywność energetyczną, kompaktowość i wydajność. Lustra MEMS działające na częstotliwościach rezonansowych zostały wybrane ze względu na ich minimalne zapotrzebowanie na energię i stabilność, pomimo ograniczeń, takich jak stałe pole widzenia (FoV) i specyficzne ograniczenia częstotliwości rezonansowej. Przeanalizowano kluczowe parametry, takie jak częstotliwość rezonansowa, pole widzenia i wymiary płytki lustra, aby zidentyfikować lustra zdolne do maksymalizacji FoV i prędkości skanowania w kompaktowym formacie. Przegląd obejmował kilka luster MEMS, w tym mechanizmy aktuacji elektrostatycznej i elektromagnetycznej, podkreślając ich zasady działania, kąty skanowania, częstotliwości rezonansowe i kompromisy projektowe***.**

Słowa kluczowe: *LiDAR noszony na ciele, lustra MEMS, częstotliwość rezonansowa, pole widzenia*

Abstarct: *This article explores the selection and characterization of MEMS mirrors for wearable LiDAR systems, emphasizing energy efficiency, compactness, and performance. MEMS mirrors operating at resonant frequencies were chosen for their minimal energy requirements and stability, despite limitations such as fixed field of view (FoV) and specific resonant frequency constraints. Key parameters, including resonant frequency, field of view, and mirror plate dimensions, were analyzed to identify mirrors capable of maximizing FoV and scanning speed within a compact form factor. Several MEMS mirrors were reviewed, including electrostatic and electromagnetic actuation mechanisms, highlighting their operating principles, scan angles, resonant frequencies, and design trade-offs.*

Keywords: *Wearable LiDAR, MEMS mirrors, resonant frequency, field of view*

1. Introduction

The development of lightweight and energy-efficient Light Detection and Ranging (LiDAR) systems is paramount for their integration into wearable devices. These systems must balance compactness with functionality to enable continuous operation without excessive power demands. Wearable LiDAR systems open a realm of possibilities, particularly in applications that require precise real-time spatial awareness. For example, these systems can empower visually impaired individuals by providing navigation assistance, obstacle detection, and enhanced spatial orientation. Beyond navigation, wearable LiDAR systems are integral to augmented reality experiences, healthcare monitoring, and environmental mapping in compact and dynamic settings.

LiDAR was first developed in the 1960s for meteorological studies, quickly extended its utility to fields such as archaeology and agriculture, where its capability to create high-resolution datasets proved invaluable. In recent years, the technology has gained prominence in domains such as autonomous vehicles, robotics, and mapping, where accurate environmental perception is critical [1] [2].

LiDAR systems function by measuring the time of flight (ToF) of laser pulses reflected from surrounding objects, allowing for precise distance calculations. Depending on how the laser beams are scanned, LiDAR systems can be categorized into two broad groups: non-scanning and scanning LiDAR. Non-scanning LiDAR, such as Flash LiDAR, illuminates an entire field of view (FoV) simultaneously and relies on an array of photodetectors to capture time-of-flight information. This design has the advantage of simplicity and resistance to mechanical vibrations but is often limited by low signal-to-noise ratio (SNR) and restricted range [1].

In contrast, scanning LiDAR systems use mechanisms to steer laser beams across a desired FoV. These systems can be further subdivided into mechanical and non-mechanical scanning approaches. Mechanical scanners typically employ rotating mirrors or motorized platforms to direct the laser beams, achieving extensive coverage but at the cost of size, weight, and energy efficiency. Non-mechanical scanners, such as optical phased arrays (OPAs), manipulate the laser direction without moving parts, offering advantages in durability and compactness [1] [3].

Among scanning LiDAR types, Microelectromechanical Systems (MEMS) mirrors have emerged as a pivotal innovation. These quasi-solid-state devices combine the advantages of solid-state and mechanical systems, steering light with high precision while maintaining compactness, low power consumption and cost efficiency. MEMS mirrors are especially well-suited for wearable LiDAR systems, where weight and energy efficiency are critical.

2. Key performance metrics

To evaluate the performance and suitability of a LiDAR system for specific applications, several key parameters must be quantified.

The minimum divergence angle of the laser beam, denoted as θ_{min}, affects the spatial resolution of the LiDAR system. It is defined as:

$$\theta_{min} = \frac{M^2 \lambda_0}{\pi w_0}$$

where λ_0 represents the laser wavelength, w_0 is the half beam waist (typically limited by the size of the MEMS mirror), and M^2 indicates the beam quality. A lower divergence angle results in better resolution, which is particularly critical for LiDAR applications requiring precision in detailed mapping.

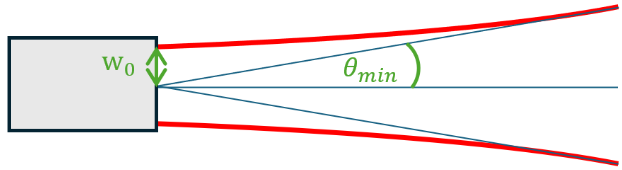

Fig. 1 Half divergence angle and half beam waist of the laser

The resonant frequency f_0 of a MEMS mirror depends on the stiffness k and mass m of the mirror. It is defined as:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

The quality factor Q is defined as the ratio of the resonant frequency f_0 to the bandwidth Δf. It is expressed as:

$$Q = \frac{f_0}{\Delta f}$$

A higher Q-factor allows for a larger scanning angle at the resonant frequency but may reduce the tolerance to changes in environmental conditions.

The position of a measured point in a MEMS-based LiDAR system is determined by the instantaneous displacement of the mirrors. In an ideal scenario, the mirrors oscillate harmonically when driven by a sinusoidal excitation signal at their resonant frequency. However, in practice, MEMS mirrors are often driven by a square wave due to its simplicity, compatibility with digital systems, and efficiency in energy transfer. While the square wave contains higher harmonic frequencies, these can influence the motion of the mirror, deviating it from pure harmonic behavior.

To minimize these deviations and approximate harmonic oscillation, low-pass filters are frequently employed to suppress higher harmonics and retain the fundamental frequency. Alternatively, the use of sinusoidal excitation can entirely eliminate higher harmonics and ensure clean harmonic motion. When the influence of non-harmonic motion is negligible, the position of the measured point can still be effectively described using equations based on ideal harmonic oscillation, ensuring accurate spatial representation in LiDAR applications. They can be defined as:

$$\theta_x(t) = \Theta_x * \sin(2\pi f_x t + \phi_x)$$

$$\theta_y(t) = \Theta_y * \sin(2\pi f_y t + \phi_y)$$

In the equations above, the angular instantaneous displacements $\theta_x(t)$ and $\theta_y(t)$ are defined, where the variables represent the following:

- Θ_x and Θ_y: The maximum amplitudes of the horizontal and vertical oscillations, respectively. These are the maximum angular displacements (in radians) the mirror reaches from its equilibrium position.
- f_x and f_y: The oscillation frequencies for the horizontal and vertical axes, respectively, defining how many complete oscillation cycles the mirror executes per second (measured in Hertz).
- t: Time, representing the progression of oscillatory motion (measured in seconds).
- ϕ_x and ϕ_y The initial phases of the horizontal and vertical oscillations, respectively, determining the angular displacement of the mirror at t=0 (measured in radians).

These parameters together describe the complete harmonic motion of the MEMS mirrors, allowing the precise calculation of the angular displacement at any point in time.

For wearable LiDAR systems, energy efficiency is a crucial consideration, making MEMS mirrors operating at their resonant frequency an optimal choice. This design minimizes energy consumption while ensuring stable oscillatory motion. However, operating at the resonant frequency introduces limitations, such as a fixed field of view (FoV), which may not suit all applications. Additionally, the resonant frequency must be carefully matched with the sensor’s measurement frequency, as higher frequencies do not always result in better performance if they exceed the sensor’s capability.

Another key factor for wearable systems is compactness. For the specific use case of wearable LiDAR, we assume that the primary goal is to achieve the largest possible FoV combined with the highest feasible resonant frequency. To address all these requirements, we focus on resonant scanning MEMS mirrors with high FoV, high resonant frequency and plate dimensions in the millimeter range.

3. 1D MEMS mirrors

The first MEMS mirror presented is described in the paper "High-Q MEMS Resonators for Laser Beam Scanning Displays" [4]. It represents a high-performance scanning mechanism suitable for a range of applications, including projection displays and LiDAR systems. This device operates on the principle of electrostatic actuation, utilizing a stacked vertical comb drive structure to achieve precise torsional oscillation. The electrostatic force generated between the comb electrodes facilitates efficient and stable motion, especially when the device is driven at its resonant frequency. The comb drive design is particularly advantageous for MEMS devices due to its ability to deliver significant force with low energy consumption.

This mirror is characterized by its high resonant frequency of 30.8 kHz, making it ideal for high-speed scanning applications. Operating at such a frequency enables rapid beam deflection, which is critical for LiDAR systems requiring high frame rates and fast data acquisition. The device achieves an impressive optical scan angle of 86 degrees, ensuring a wide field of view (FoV) suitable for capturing spatial information across a broad area. The combination of a high resonant frequency and wide FoV makes this mirror an excellent candidate for dynamic environments where rapid and accurate spatial mapping is required.

One of the defining features of this MEMS mirror is its high Q-factor, measured at 26,800. This high Q-factor reflects the efficiency of the system, as it minimizes energy losses during oscillation. This efficiency is further enhanced by vacuum encapsulation, which significantly reduces gas damping effects. The encapsulation not only improves the energy efficiency of the mirror but also contributes to the stability and predictability of its motion, which are critical for precision applications.

In terms of physical characteristics, the mirror plate dimensions are compact, with a width of 0.8 mm and a thickness of 60 µm. This small form factor makes the device particularly well-suited for wearable LiDAR systems, where size and weight constraints are paramount. Compact design also facilitates integration into devices requiring portability and unobtrusiveness, aligning well with the goals of wearable technology.

Another notable feature is the implementation of vacuum encapsulation at the wafer level, which not only reduces gas damping but also protects the device from contamination during operation. The use of titanium thin-film getters within the encapsulation process ensures long-term vacuum stability, further improving the mirror's efficiency and durability. This innovative approach demonstrates a practical solution for addressing the challenges of high-speed MEMS operation under varying environmental conditions.

Moreover, the fabrication process leverages advanced silicon micromachining techniques, including deposition of low-stress polysilicon layers and deep reactive-ion etching. These methods enable precise control over the mirror's geometry and mechanical properties, ensuring consistent performance and reliability. The resulting mirror design achieves a theta-D product of 17.3 mm·degrees, sufficient for high-definition resolution applications, such as HD720 raster-scanning displays. These attributes make it a compelling choice for both consumer and industrial applications requiring compact, high-performance optical systems.

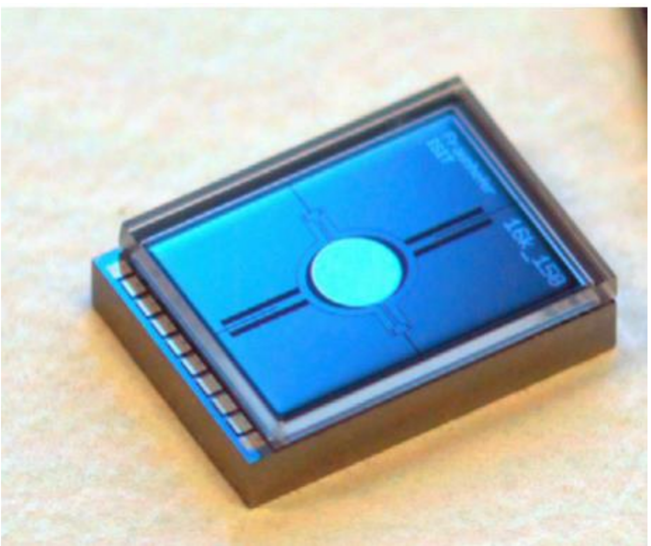

Fig. 2 High-Q MEMS Resonator for Laser Beam Scanning Displays

The second MEMS mirror presented, a flat high-frequency scanning micromirror [5], is based on the Staggered Torsional Electrostatic Combdrive (STEC) mechanism, designed to achieve high-speed optical scanning with large angular deflections. This mirror operates by applying an electrostatic voltage between two layers of single-crystal silicon separated by a thin silicon dioxide layer. The electrostatic force generated between the moving and fixed comb teeth produces a torque that tilts the mirror, achieving both static positioning and resonant scanning. The torsional hinges connected to the bottom silicon layer provide the restoring force required for its oscillatory motion.

The mirror demonstrates an optical scan angle of 24.9° and operates at a high resonant frequency of 34 kHz, making it highly suitable for applications requiring rapid scanning. This performance allows the mirror to achieve a total optical resolution of 350 pixels, which is near the diffraction-limited resolution for 655 nm light. The high scanning speed and precision make this design particularly well-suited for compact and high-performance LiDAR systems.

The structural design incorporates a 550 µm-diameter mirror, fabricated using advanced silicon micromachining techniques, including deep reactive-ion etching and wafer bonding. The mirror's thickness is 50 µm, ensuring its structural integrity while minimizing dynamic deformation during high-speed oscillations. Measured deformations of less than 30 nm ensure that the mirror maintains its optical flatness, which is crucial for preserving beam quality and minimizing divergence.

This MEMS mirror is also energy efficient, with a power consumption of approximately 6.8 mW, primarily attributed to charging and discharging parasitic capacitances and losses in the power conversion. Its vacuum packaging reduces air damping, further improving its efficiency and performance reliability.

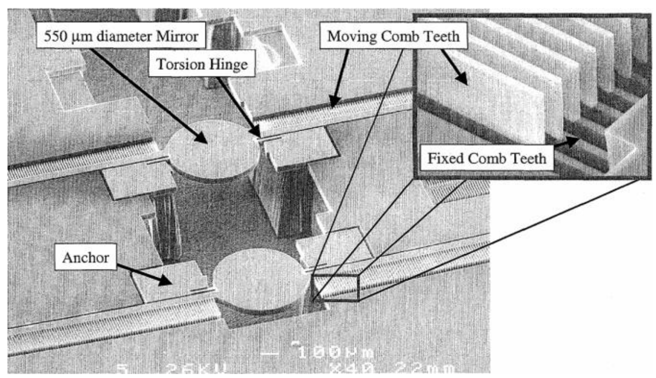

Fig. 3 Scanning Electron Micrograph of two STEC micromirrors

4. 2D MEMS mirrors

MEMS mirror presented in the article [6] is a bi-axial micro-scanner designed for laser beam scanning applications, particularly in projection displays. This mirror operates through electrostatic actuation, using comb-drive electrodes to generate the torque necessary for its oscillatory motion. The device also incorporates capacitive sensing, allowing simultaneous position monitoring and driving of the mirror using shared electrodes, which minimizes the complexity of the design.

The micro-scanner employs a gimbaled structure, where a circular reflective plate (1 mm in diameter) is connected to a rectangular frame through torsional beams, enabling horizontal oscillation. The frame itself is connected to the base structure via another set of torsional beams for vertical oscillation. This design allows independent two-dimensional scanning, crucial for forming stable Lissajous scanning patterns in applications like projection systems.

The measured resonant frequencies for the vertical and horizontal axes are 1.4 kHz and 21.9 kHz, respectively, with optical scan angles of 22.5° and 40°. This high-speed operation, combined with a compact size of 4.3 mm × 4.3 mm × 70 μm, makes the mirror suitable for integration into compact optical systems. The reflective surface of the mirror is coated with a thin aluminum layer, enhancing its optical efficiency.

The fabrication of the device employs silicon-on-insulator (SOI) micromachining techniques, ensuring precise dimensional control and structural integrity. The integration of capacitive sensing and electrostatic actuation within the same structure leverages frequency multiplexing to separate driving and sensing signals, enabling efficient closed-loop control through a phase-locked loop (PLL). This ensures that the mirror remains in resonance even under varying environmental conditions, which is critical for maintaining consistent scanning performance.

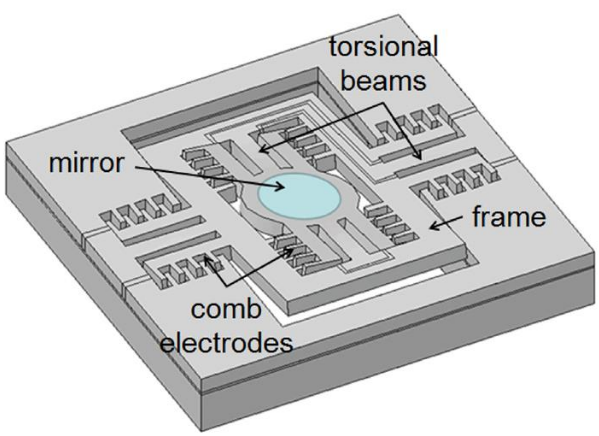

Fig. 4 Bi-axial micro-scanner with a gimbaled microstructure

The MEMS mirror described in the study: “Two-Axis Electromagnetic Microscanner for High Resolution Displays. J. Microelectromech” [7] is a bi-axial scanning device designed for high-resolution display systems, including retinal scanning displays. It operates using electromagnetic actuation, where a current-carrying coil integrated into the mirror interacts with an external magnetic field to generate Lorentz forces. These forces induce torsional motion around two orthogonal axes, enabling precise two-dimensional scanning.

The mirror is mounted on a gimbaled structure, which allows independent rotation for horizontal and vertical scanning. This design ensures stable and predictable motion necessary for high-resolution applications. The device achieves optical scan angles of 65° for the horizontal axis and 53° for the vertical axis, providing a wide field of view suitable for detailed imaging. The resonant frequencies of the system are tuned to allow high-speed operation, ensuring rapid and consistent performance across scanning cycles.

Fabricated using MEMS technology, the mirror exhibits compact dimensions, facilitating its integration into small-scale systems such as wearable or portable devices. The electromagnetic actuation mechanism provides large angular deflections, enhancing the resolution of the scanned image. However, this method requires an external magnetic field, which can increase the complexity of system integration and may introduce power consumption considerations.

Despite its dependency on a magnetic field, this MEMS mirror demonstrates exceptional performance in terms of speed, resolution, and field of view. Its compact design and robust fabrication make it a strong candidate for advanced display and imaging applications requiring precise and dynamic beam scanning.

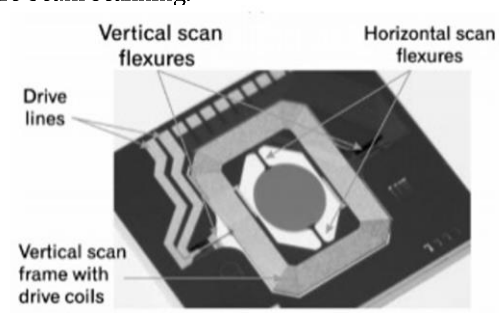

Fig. 5 Electromagnetic actuators

5. Summary and conclusions

The exploration of MEMS mirrors for wearable LiDAR systems has demonstrated their significant potential in combining compactness, energy efficiency, and precise optical scanning. These mirrors, particularly those operating at resonant frequencies, offer an optimal balance of performance and low energy consumption, making them ideal for wearable applications. However, challenges such as limited fields of view and sensitivity to environmental factors require further refinement.

From the analyzed actuation mechanisms, both electrostatic and electromagnetic approaches offer distinct advantages that could be leveraged depending on the specific application requirements. Electrostatic mirrors excel in energy efficiency and compactness, while electromagnetic mirrors provide greater robustness, making them viable candidates for wearable LiDAR in dynamic environments. The choice of mechanism should be guided by the specific demands of the wearable device, such as vibration resistance, field of view, and power constraints.

Future research should focus on enhancing the adaptability of both actuation types to wearable applications, particularly in terms of stability under real-world conditions. Advancements in materials, design, and integrated feedback systems could further improve performance, ensuring reliable operation even in challenging environments. Additionally, exploring optimized combinations of these mechanisms or novel approaches could lead to breakthroughs in wearable LiDAR technology, enabling more versatile and effective devices.

References

1. Wang, D.; Watkins, C.; Xie, H. MEMS Mirrors for LiDAR: A Review. Micromachines 2020, 11, 456. https://doi.org/10.3390/mi11050456
2. T. Miyasaka, Y. Ohama and Y. Ninomiya, "Ego-motion estimation and moving object tracking using multi-layer LIDAR," 2009 IEEE Intelligent Vehicles Symposium, Xi'an, China, 2009, pp. 151-156, doi: 10.1109/IVS.2009.5164269. https://ieeexplore.ieee.org/document/5164269
3. P. F. McManamon et al., "A Review of Phased Array Steering for Narrow-Band Electrooptical Systems," in Proceedings of the IEEE, vol. 97, no. 6, pp. 1078-1096, June 2009, doi: 10.1109/JPROC.2009.2017218. https://ieeexplore.ieee.org/document/4939409
4. Hofmann, U.; Janes, J.; Quenzer, H.-J. High-Q MEMS Resonators for Laser Beam Scanning Displays. Micromachines 2012, 3, 509-528. https://doi.org/10.3390/mi3020509
5. Conant, R.A.; Nee, J.T.; Lau, K.Y.; Muller, R.S. A flat high-frequency scanning micromirror. In Proc. Hilton Head Solid-State Sensor and Actuator Workshop; University of California: BerkeleyBerkeley, CA, USA, 2000; pp. 6–9.
6. Hung,A.C.-L.; Lai, H.Y.-H.; Lin, T.-W.; Fu, S.-G.; Lu, M.S.-C. An electrostatically driven 2D micro-scanning mirror with capacitive sensing for projection display. Sens. Actuators A Phys. 2015, 222, 122–129. https://www.sciencedirect.com/science/article/pii/S0924424714004427?via%3Dihub
7. Yalcinkaya, A.D.; Urey, H.; Brown, D.; Montague, T.; Sprague, R. Two-Axis Electromagnetic Microscanner for High Resolution Displays. J. Microelectromech. Syst. 2006, 15, 786–794. https://ieeexplore.ieee.org/document/1668174