MEMS based micromirror system for deployment in optical beam steering systems used in Quantum Information Processing

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Abstract

The aim of this study is to highlight the utility and applicability of *Microelectromechanical* systems (MEMS) technology in addressing the existing challenges of precision control of beams in performing manipulation of two dimensional atomic systems or qubit states in Quantum Information Processor Implementations. This study specifically focuses on the applicability of a controllable MEMS based Micromirror that guides a laser beam to address multiple qubit locations in a two-dimensional trapped lattice; an application of pertinent interest to Experimental Quantum Computation.

Background and Motivation

The experimental implementation of Quantum Information Processors harnesses the internal states of trapped ions, photons or neutral atoms to represent ***qubits***. The coherent control and manipulation of these states is integral for performing computation or other measurements. Hence the precise control of laser beams as a part of an *'Optical beam steering'* system is a pertinent challenge because of the restrictions imposed on the operational wavelength of qubits, the decoherence and dephasing times etc.

Drawbacks of the existing system

Existing beam steering systems exploit acousto-optic deflectors and electro-optic deflectors. Acousto-Optic deflectors have a heavy power consumption because they require high RF drive power and induce small frequency shifts. Electro-Optic deflectors on the other hand have very high operational voltages and a limited angular range. MEMS have been explored as an alternative, to satiate the existing challenges and provide a more compact and flexible beam steering functionality. In this report we explore the properties of a Micromirror.

Proposed Design and Architecture

The MEMS mirror consists of a mirror plate that rotates about two torsional springs as shown below [**Figure** 1]. It is electrostatically actuated by means of a grounded mirror plate and underlying electrodes. The mirror was made out of Aluminium (**Uvarov et al.** [**3**]), owing to its optical properties so as to enhance reflectivity in the beam steering system and thermal stability (**Stankevič and Šimkevičius** [**2**]).

Packages and Modules used (COMSOL)

Thermoviscous Acoustics, Transient(labelled as ***tatd*** in the graph), MEMS module, Pressure, Temperature and other variables

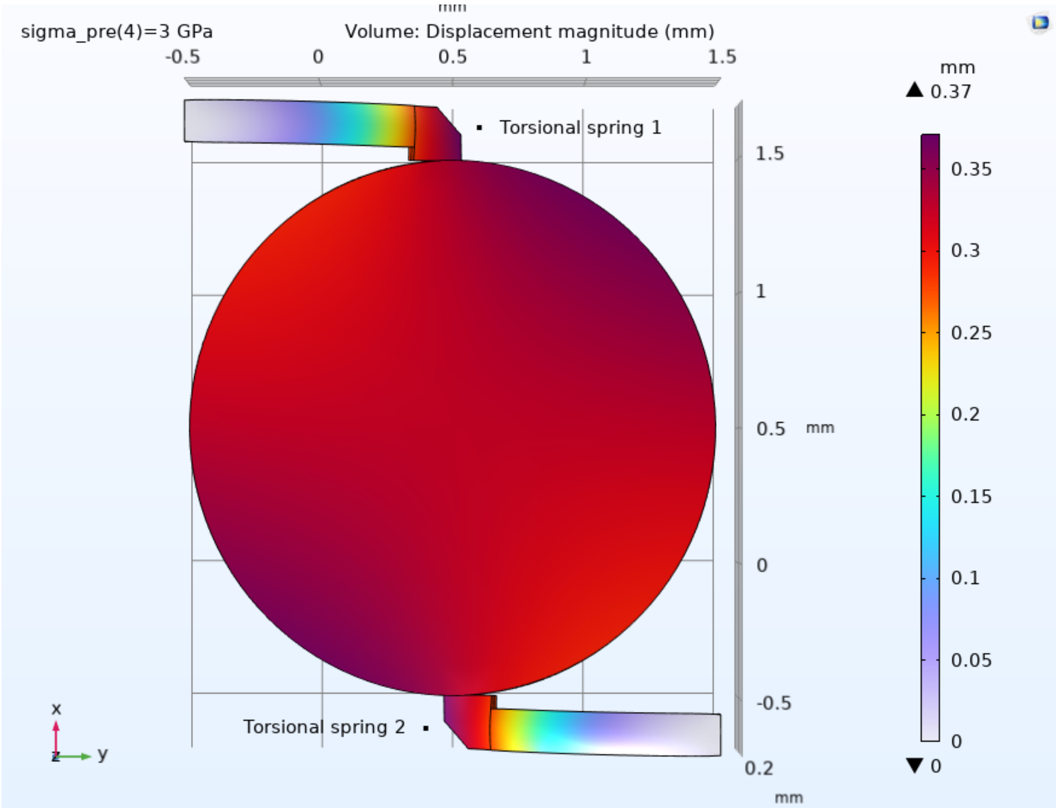

Figure 1: Structural Design of the micro-mirror

The dynamic characteristics of the above design can be modeled as a damped harmonic oscillator with resonance frequency $\boldsymbol{\omega}$. where;

$$\omega = 2K/I$$

where, $\boldsymbol{K}$ is the torsional stiffness for one of the mirror's springs and $\boldsymbol{I}$ is the moment of inertia of the mirror plate.

How is this applicable to Two dimensional atomic systems in Quantum Information ?

Neutral atom gate operations require a switching time (time required to move from the ground to excited state) of around 1μs. For optimal control, the device must have the ability to reduce the settling time in a two level system and maintain near critical damping. This can be successfully achieved by increasing the resonance frequency $\boldsymbol{\omega}$ of the system. The rest of the parameters of precision control namely the maximum tilt angle are adjusted by the optical system arrangement.

According to (**Knoernschild et al.** [1]) the micromirror is deployed in the following optical set-up:

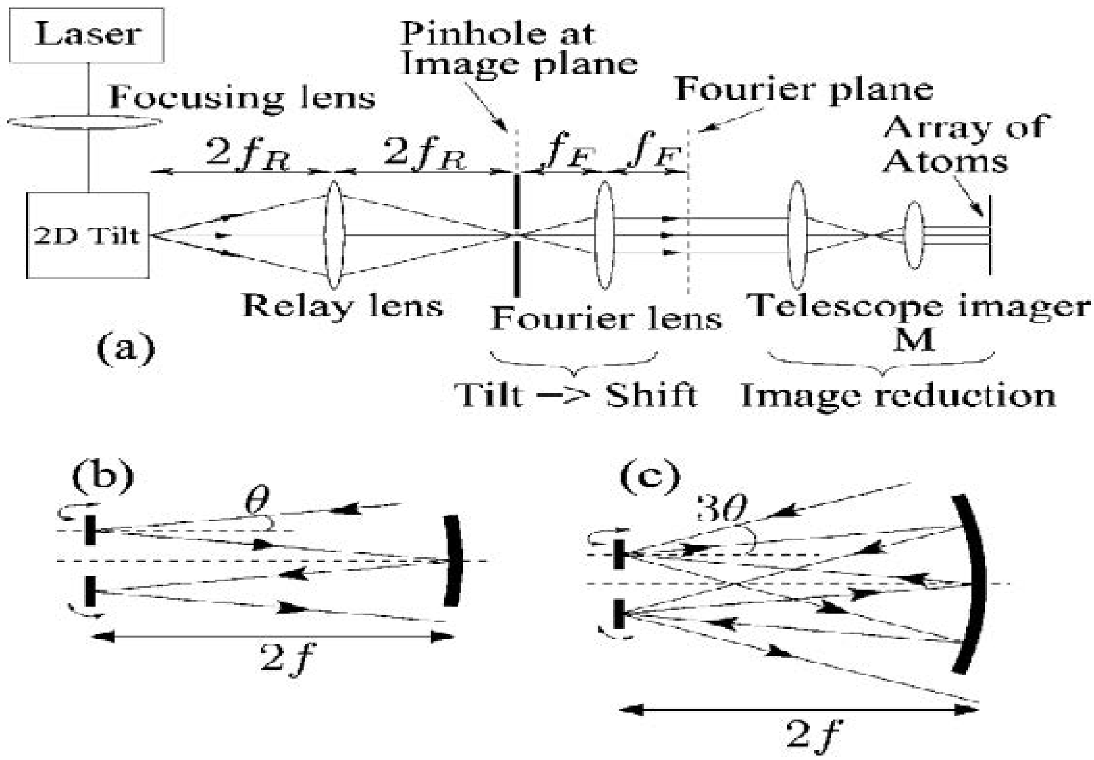

Figure 2: **Schematic depiction of the MEMS based micro-mirror deployed in the beam steering system as described by the work of (Knoernschild et al. [1]). b) and c) depict the optics of the single bounce and double bounce systems through ray diagrams.**

The micromirror of study in this report is a part of the $2D$ Tilt system shown in the above optical set-up. The micromirror system placed in the $2D$ title box above reflects off the input beam that is then imaged through a $\boldsymbol{2f_R - 2f_R}$ relay lens onto an image plane facilitating optical alignment.

Mirror size and maximum tilt angle are determined by the optical system. Defining a variable $\boldsymbol{\zeta = f_F/M}$ (M is the magnification constant that is achieved through the Telescope imager set-up above) and incorporating an $\boldsymbol{n}$-bounce system (α refers to the lattice constant of a neutral atom) , the beam waist at the MEMS mirror ($\boldsymbol{\omega_M}$) and the maximum required mechanical tilt max are given by;

$$\omega_M = \frac{\lambda f_F}{\pi \omega_0'} = \frac{\lambda}{\pi \omega_0}\zeta, \tag{1}$$

$$(\Delta\theta)_{max} = \frac{\alpha'}{f_F}\frac{N-1}{4n} = \frac{\alpha}{\zeta}\frac{N-1}{4n}, \tag{2}$$

From eq. (1) and eq. (2) we can deduce that,

$$\omega_M \propto 1/\left(\Delta\theta\right)_{max}$$

Based on the above analysis, the following parameters were considered to model the micromirror in COMSOL:

Center frequency for analysis	f_0	$10.7kHz$
Frequency range	Δf	$500Hz$
Viscous boundary layer thickness in air at f_0	d_{visc}	$0.22mm * \sqrt{100Hz/f_0}$
Mirror thickness	h_{mirror}	$1\mu m$
Resonance frequency (eigenfrequency study)	f_{num}	$(10470 + 148.49i)Hz$
Resonance frequency	$f_r(real)$	10470Hz
Resonance half power width (frequency sweep)	df_r	$295.87Hz$

Results

Considering these parameters and analysis, the following were the images and plots obtained from the COMSOL console:

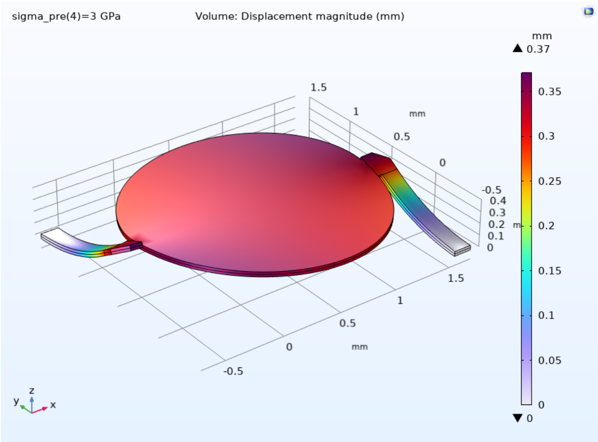

Figure 3: Displacement of the Aluminium based micro-mirror under $3GPa$ stress (View 1).

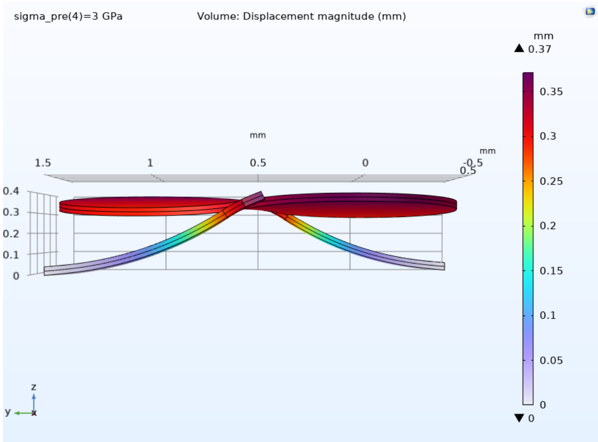

Figure 4: Displacement of the Aluminium based micro-mirror under $3GPa$ stress (View 2).

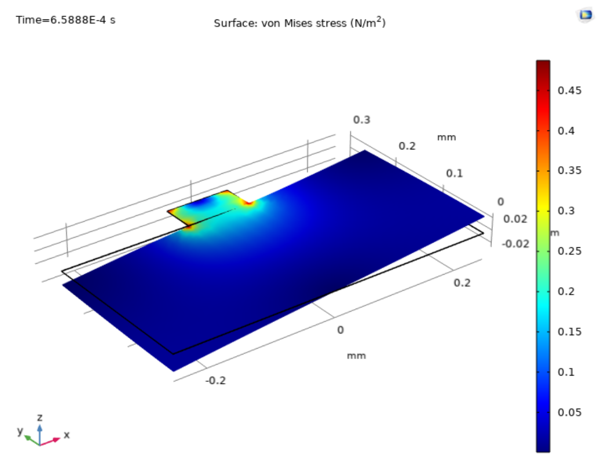

Figure 5: The displacement of the $2D$ tilt box containing the micromirror. The deflection as seen at time $6.588 \times 10^{-4}s$ (View 1).

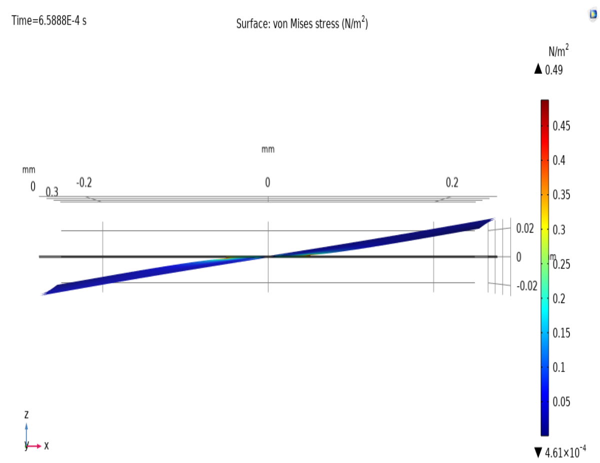

Figure 6: The displacement of the $2D$ tilt box containing the micromirror. The deflection as seen at time $6.588 \times 10^{-4}s$ (View 2).

The subtle variations on the surface of the micromirror are visible in a short time frame implying the convenience in performing tilt. As can be seen from the above plots, especially [**Figure** 3] and [**Figure** 4], the displacement of the micromirror from its mean position especially on application of a large amount of stress , 3GPa for simulating the system is in the order of $(1/100)^{th}$ of a millimeter. Such stability and resilience is necessary while dealing with control of neutral atom systems owing to the sensitivity of the coherence and dephasing time of a qubit in the ecosystem of experimentation, especially in Open Quantum Systems.

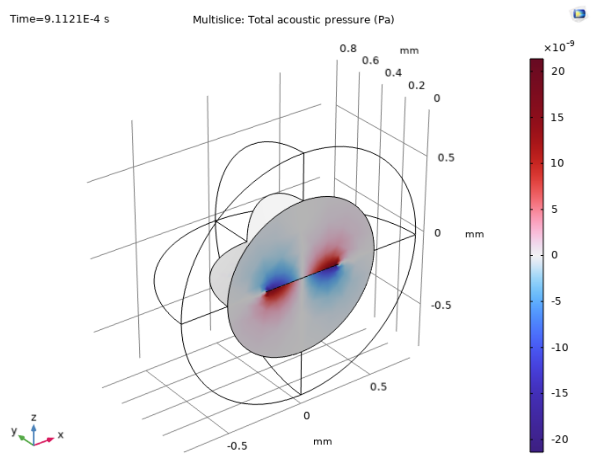

Figure 7: Plot of the total acoustic pressure variations at time $9.112 \times 10^{-4}s$

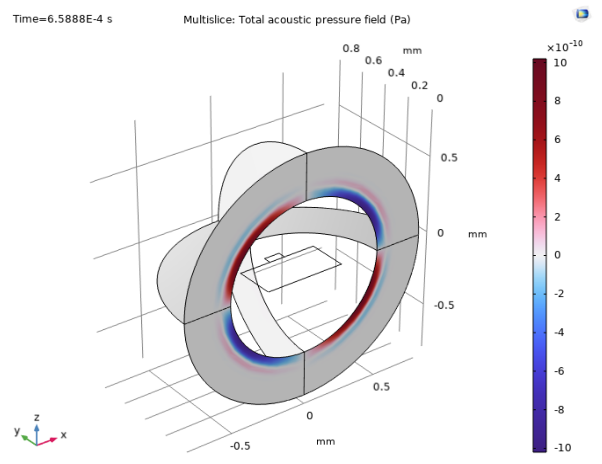

Figure 8: Plot of the total acoustic pressure at time $6.588 \times 10^{-4}s$

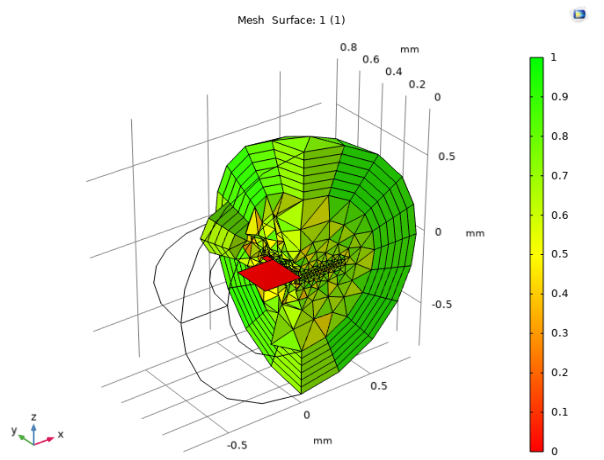

Figure 9: Mesh surface level view

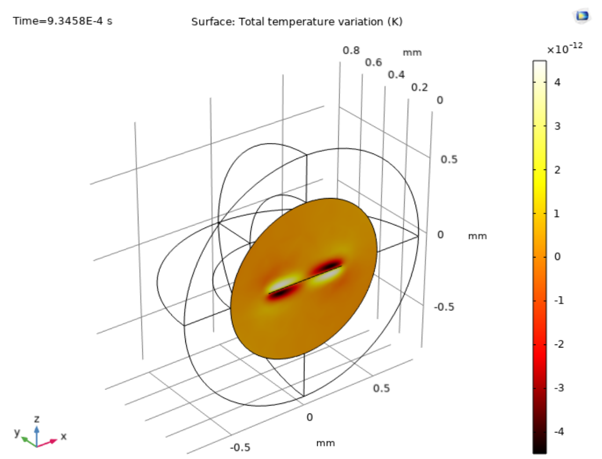

Figure 10: Temperature variation across the surface of the micromirror in K

[**Figure** 10] shows the temperature variation throughout the surface of the micromirror while being simulated, *i.e.*, during the process of actuation while it is vibrating. The variation is in the order of $10^{-12}K$ which ensures thermal stability of the device. A higher variation would imply overheating of the mirror surface that might affect beam reflections.

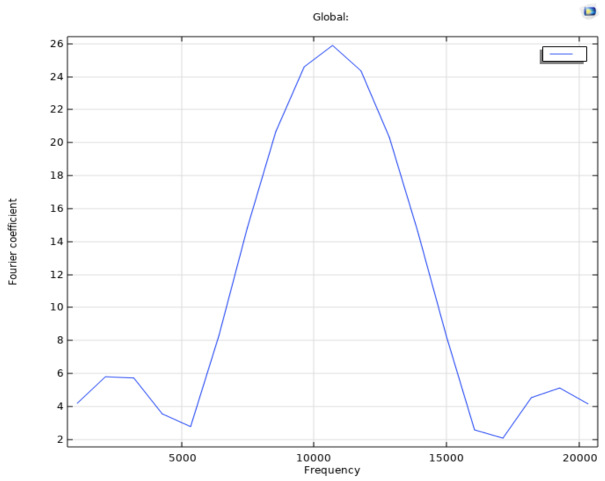

Figure 11: The variation of Frequency with the Fourier coefficient

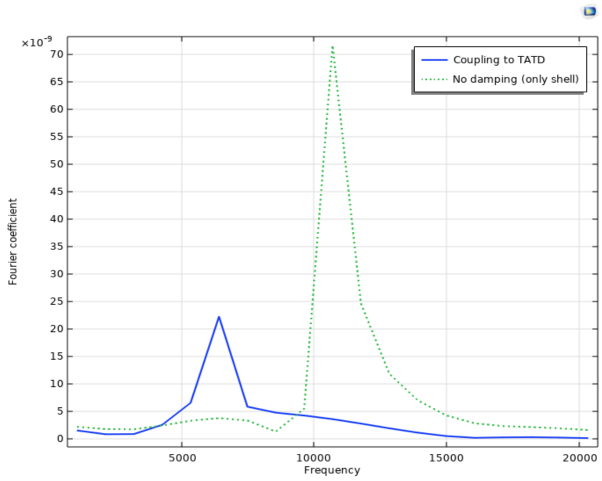

Figure 12: The variation of Frequency with fourier coefficient considering the surrounding air model as well as the isolated micromirror

[**Figure** 11] and [**Figure** 12] are in tandem with the results of the paper by **Knoernschild et al.** [**1**] who describe the residual intensities at neighboring qubit locations represented here by the frequency values to the right and left of the peak were measured to be below the peak output intensity (around 11000 Hz here) consistent with the Gaussian beam directions. These demonstrate that the analog actuation volatges controlled by digital circuits facilitate the fine shifting control.

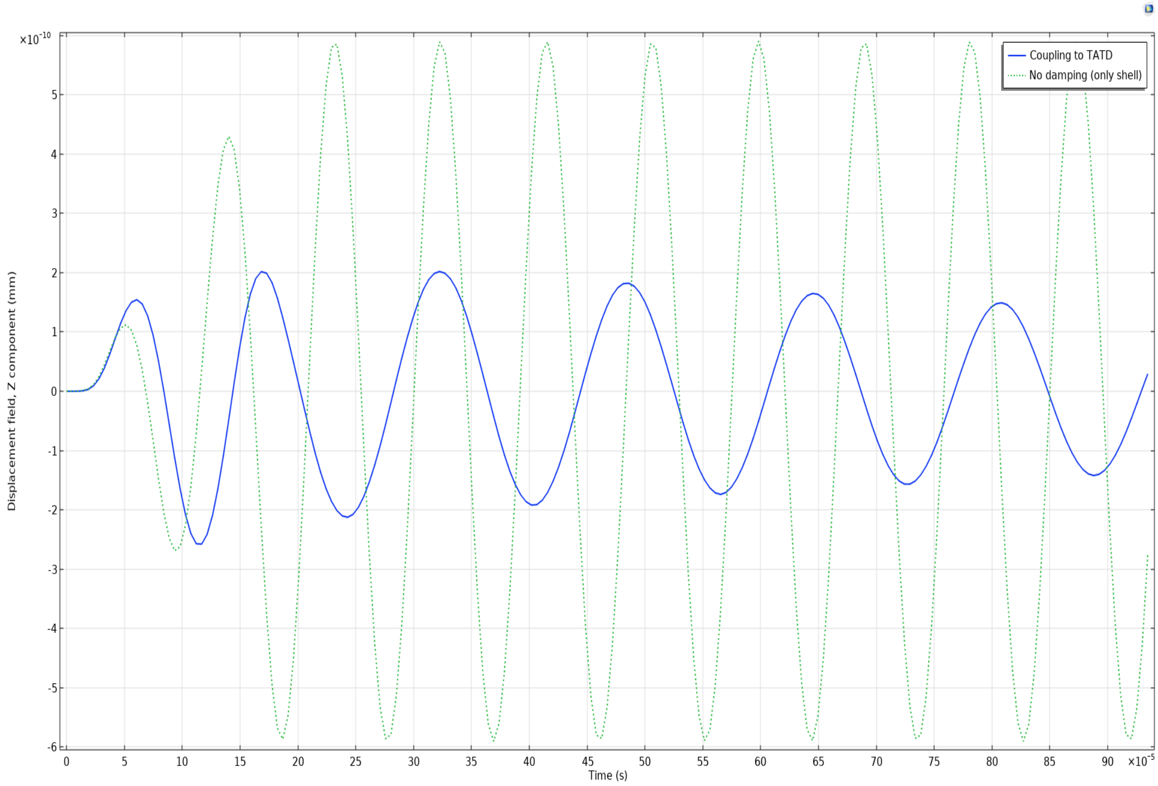

Figure 13: **The displacement field is modeled in mm comparing the two cases; coupled system** *vs.* **the isolated system. This is in accordance with the goal of deployment that required minimizing settling time of the neutral atom state by maintaining near critical damping.**

Conclusion

The above results and analysis depict the suitability of deploying Aluminium based Micromirrors for Optical beam steering systems especially in two dimensional atomic systems that are highly sensitive to the surrounding ecosystem that might affect their dephasing and switching times. The stability of Micromirrors when subject to thermal, acoustic, electrical and other vibrational transients is remarkable in the context of this application. Introducing an array of micromirrors and using other techniques like beam reduction optics as mentioned by **Knoernschild et al.** [1] can easily scale the measured results at the Fourier Plane down to the necessary dimensions at the atom locations.

References

[1] C. Knoernschild, C. Kim, B. Liu, F. P. Lu, and J. Kim. Mems-based optical beam steering system for quantum information processing in two-dimensional atomic systems. *Opt. Lett.*, 33(3):273–275, Feb 2008. doi: 10.1364/OL.33.000273. URL `https://opg.optica.org/ol/abstract.cfm?URI=ol-33-3-273`.

[2] V. Stankevič and Šimkevičius. Application of aluminum films as temperature sensors for the compensation of output thermal shift of silicon piezoresistive pressure sensors. *Sensors and Actuators A: Physical*, 71(3):161–166, 1998. ISSN 0924-4247. doi: https://doi.org/10.1016/S0924-4247(98)00178-2. URL `https://www.sciencedirect.com/science/article/pii/S0924424798001782`.

[3] I. Uvarov, R. Selyukov, and V. Naumov. Testing of aluminium and its alloys as structural materials for a mems switch. *Microsystem Technologies*, 26, 06 2020. doi: 10.1007/s00542-020-04748-2.