A New LIDAR Method using MEMS Micromirror Array for the JEM-EUSO mission

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***Abstract*. LIDAR (LIght Detection And Ranging) is an important method in measuring atmospheric transparency that is used to correct fluorescence light yield from extensive air showers. For the JEM-EUSO (Extreme Universe Space Observatory on Japanese Experimental Module) mission to observe ultra-high cosmic rays at the ISS (International Space Station) orbiting at 400 km altitude the method is used also to measure the cloud-top altitude which is one of crucial information to estimate the energy of primary cosmic rays. A novel type of space-LIDAR system has been proposed for JEM-EUSO telescope. This system utilizes an array of rapid MEMS (Micro-Electro-Mechanical Systems) micromirrors that allow shooting the source laser light in any direction in the view of the telescope. The detection of backscattered photons is made with the JEM-EUSO telescope. The key element of the rotatable micromirrors is the electrostatic analog two-axes actuators with resonance frequencies of about 1 kHz. The micromirror plates installed on top of the actuators are designed to have high-quality surface roughness (lower than 4 nm in average) and robustness in a long-term exposure to the LIDAR beam. A prototype of the micromirror array was successfully tested on the ISS. The LIDAR concept, system design, and initial test results are presented.**

***Keywords*: JEM-EUSO, LIDAR, MEMS Micromirror**

I. INTRODUCTION

For the JEM-EUSO telescope which is an observatory on board the International Space Station (ISS) to observe fluorescence light from extensive air showers in the earth's atmosphere it is important to continuously monitor atmospheric transparency as the region of atmosphere in the view of the telescope changes along the orbit at 400 km altitude [1]. It is also important for JEM-EUSO to continuously measure the cloud-top altitude where the fluorescence and Cerenkov light from air showers are reflected in most of cases, providing the mark of shower end which is used to constrain the shower profile and consequently to determine the energy of primary cosmic ray.

Installed together with the infrared camera in the JEM-EUSO telescope the LIDAR system provides a tool for calibration of the JEM-EUSO detection efficiency, using the molecular backscatter signal from the laser beam and/or the signal scattered from cloud top and surface, and absolute measurements of the range to the top of the opaque clouds in the FOV of the JEM-EUSO telescope [2]. The direct observation data of the cloud-top altitude obtained by the LIDAR serves as calibration data from the infrared camera because of the better ranging resolution of the LIDAR which is about 30 m. From data by both the infrared camera and the LIDAR, accurate 3-dimensional cloud distribution and cloud-top altitude are determined.

A LIDAR system is an assembly of a laser beam source, robotic steering mechanics of the light transmitter, photon detector, and the control electronics. In the JEM-EUSO mission, the proposed new LIDAR method has the special beam reflector which is rotatable rapidly in two-axes so that the direction of the LIDAR beam can be instantaneously changed to any direction in the view of the telescope. Such a reflector can be fabricated using the optical MEMS(Micro-Electro-Mechanical Systems) technologies. The technology has been widely applied in many fields including most commonly used optical device which is micromirror with the typical size of hundreds of micrometers.

The MEMS-mirror beam steering method has several advantages over the conventional mechanical ways especially in space applications like the JEM-EUSO or the TUS telescopes [3]. The MEMS LIDAR concept,

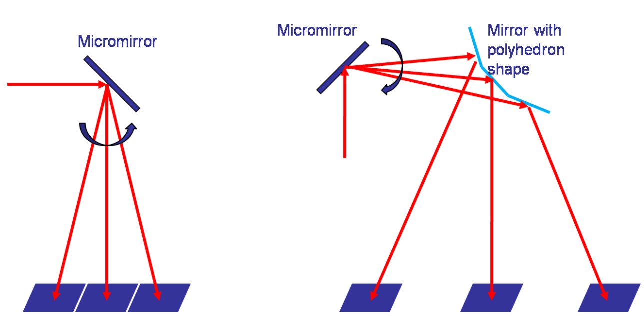


Fig. 1: MEMS micromirror LIDAR concepts : single mirror operation (left) and extended angle mode (right).

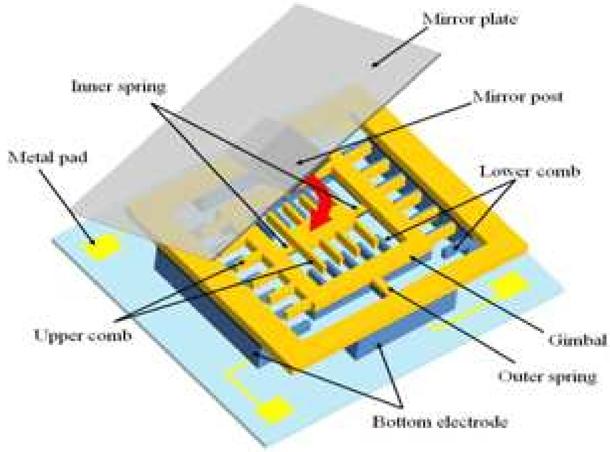


Fig. 2: A schematic view of a micromirror for two-axes rotation

the design and fabrication, and initial test results are discussed in the following sections.

II. System Concept and Operation Modes

The key idea of the proposed LIDAR method is in the instantaneous control of the beam direction using MEMS micromirrors. The array of the mirrors is a type of optical MEMS devices that ranges from a micron to a centimeter in size that combine mechanical, electrical, and optical components. Various types of optical MEMS devices have been successfully used in a wide range of applications, including optical communications, display systems, biomedical instrumentation, and adaptive optics [4]. Especially, many nice features like small size, high robustness, and low power consumption make the devices just suitable for space optical systems [5]. The most commonly used optical MEMS device is the micromirror, which has rapid tilting speed and high reliability compared with large conventional mirrors.

The operation scheme is shown in Fig. 1 for the single mirror mode (left) and for wide-angle mode (right). The mirror plates are rapidly rotated by the electrostatic force applied in the analog two-axes actuators which the mirror plates are attached to. The electrostatic force is controlled by variable applied voltage. In the single mirror mode total range of beam shooting direction is limited to the maximum titling angle of the actuators which is about 8 degree. The possible range of beam direction can be further increased with additional fixed mirror structure, as shown in Fig. 1 (b), covering entire FOV of the JEM-EUSO telescope.

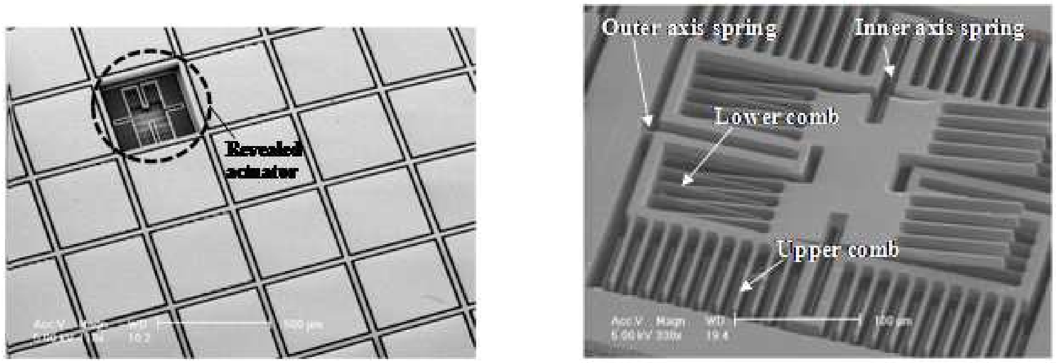
The array of micromirrors are operated in a couple of modes, depending on the purpose of the measurement. In the first mode (Scanning mode) the LIDAR scans periodically the atmospheric condition in the FOV by shooting the beam to several fixed positions. The second is the targeting mode that the beam is directed to the position of candidate shower event immediately after the JEM-EUSO third level trigger is issued. The detection of backscattered LIDAR photons is made with the JEM-EUSO telescope.

III. MEMS Micromirror Design

The MEMS micromirror is composed of three parts : a pair of tiny vertical combs which are electrostatic actuators, a mirror plate as a reflector, and bottom electrodes on glass substrate to apply a voltage. A schematic view of the mirror actuator and core actuating mechanism is shown in Fig. 2 [6].

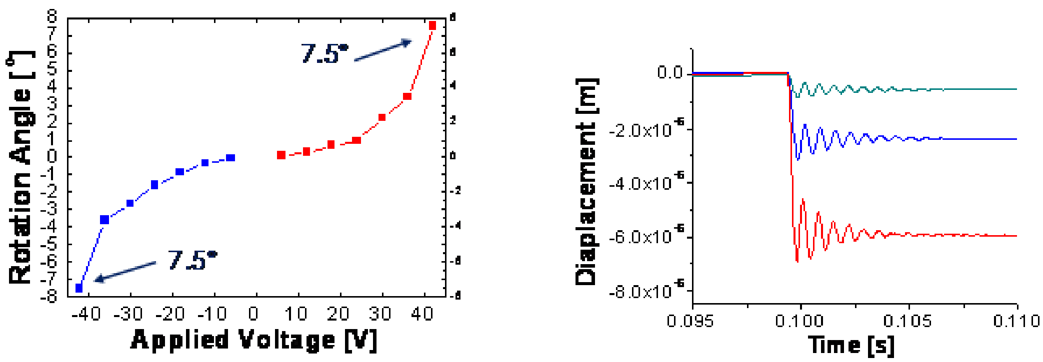
The vertical comb actuation part is fabricated on a Silicon-On-Insulator (SOI) wafer. The bottom silicon layer of the SOI wafer is patterned to form the comb electrodes attached on glass wafer to which the actuation voltage is applied. And the top silicon layer is used as the ground electrode that is isolated by middle silicon thermal oxide layer. The moving part of the actuator has a gimbal-like frame and two orthogonal pairs of springs allow the mirror plate to be tilted independently in two orthogonal directions. In this way the tilt angle of the micromirror can be made in any direction. The operation of the actuators are controlled by the dedicated driver circuit that communicates with the central data acquisition electronics of the JEM-EUSO.

The mirror plate is formed at the inner plate of the actuator using a wafer bonding process and the surface is coated with an Al layer. High reflectivity and high-quality surface roughness is very important to obtain well-focused beam and also to protect the mirror from any possible damage from a long exposure to the LIDAR beam. The actuator part and the glass substrate with electrical lines are bonded together to make electrical contact between the comb electrodes and addressing lines. The actuator and addressing lines can be hidden behind the mirror plate, resulting in a high fill-in factor of 84 % [7].



(a) Micromirror Array (b) the Comb Actuator

Fig. 3: SEM images of the fabricated micromirror



(a) Micromirror Array (b) the Comb Actuator

Fig. 4: Measured characteristics of the micromirror

IV. Fabrication and Performance of MEMS Micromirror

A prototype array of 8 x 8 micromirrors were successfully fabricated with the design concept described in the previous sections. Fig. 2 shows the SEM (Scanning Electro Microscope) images of the micromirror [6]. The surface of mirror array is shown in the left (a). One of the mirror plates is opened to show the actuator under the plate. The closer view of the comb actuator is shown in Fig. 2 (b).

The performance has been tested under several conditions. First, the rotation angle is checked as a function of the bias voltage. The result is shown in Fig. 4 (a) The micromirror has up to about 7 deg of static tilting angle. And the dynamic response of the mirror is shown in Fig. 4 (b). The torsional resonance of the structure was found to be at frequencies of 2 kHz and 1 kHz for two rotational axes. The rotation time is less than 5 ms, which is in the level of the designed performance. [8][9].

Space is a unique environment that may cause severe failures of MEMS devices. The micromirrors were designed to sustain their performance in the shock and vibration environment of the ISS. The performance of the fabricated micromirror was tested for shock and vibration, stiction, outgassing from depressurization and heating, and electrostatic charging effects. No degradation of the micromirror performance was found after the space environment tests. In addition to the ground test, a test bed instrument equipped with the micromirrors was delivered to the ISS Russian Segment (RS) and tested in the pressurizes module for one week starting from April 11, 2008. The results demonstrate that the proposed micromirrors are suitable for optical space systems. And the successful operation of the micromirror in the ISS proved the validity and applicability of the ground environment test procedure for space qualification. Details in the test are described in Ref. 10.

V. Conclusion

A novel type of space-LIDAR method is being developed using the optical MEMS technology for the JEM-EUSO telescope. The key characteristics is in the steering method for the laser beam where an array of MEMS micromirrors rotating rapidly in two axes reflects the beam from the UV source to any direction in the view of telescope. The operation of micromirrors is controlled by the steering electronics which is a part of DAQ electronics. The feasibility of the application has been confirmed as the fabrication of the MEMS mirrors and the space test at the ISS have been successfully finished. The remaining task in finalizing the method is to check the long term stability of the mirror and the actuators under the radiation of laser beam.

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