A Microshutter-based Field Selector for JWST's Multi-Object Near Infrared Spectrograph

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ABSTRACT

One of the James Webb Space Telescope's (JWST) primary science goals is to characterize the epoch of galaxy formation in the universe and observe the first galaxies and clusters of galaxies. This goal requires multi-band imaging and spectroscopic data in the near infrared portion of the spectrum for large numbers of very faint galaxies. Because such objects are sparse on the sky at the JWST resolution, a multi-object spectrograph is necessary to efficiently carry out the required observations. We have developed a fully programmable array of microshutters that will be used as the field selector for the multi-object Near Infrared Spectrograph (NIRSpec) on JWST. This device allows apertures to be opened at the locations of selected galaxies in the field of view while blocking other unwanted light from the sky background and bright sources. In practice, greater than 100 objects within the field of view can be observed simultaneously. This field selection capability greatly improves the sensitivity and efficiency of NIRSpec. In this paper, we describe the microshutter arrays, their development, characteristics, fabrication, testing, and progress toward delivery of a flight-qualified field selection subsystem to the NIRSpec instrument team.

Keywords: Field selector, JWST, Spectrograph, Near Infrared

1. INTRODUCTION

The James Webb Space Telescope (JWST) will be a cold 6.5 m segmented telescope in space optimized for observations at infrared wavelengths. Its purpose is to significantly advance our understanding of stars, planetary systems, and the formation and evolution of galaxies from the time of the first luminous objects in the universe. To accomplish these goals, JWST has a complement of instruments for imaging and spectroscopy. The Near-Infrared Spectrograph (NIRSpec), a multi-object spectrograph (MOS), will provide spectral information on selected objects at wavelengths in the range 0.6-5 μm. NIRSpec can operate with resolutions, R$\sim$100 over its entire operating range and R$\sim$1000 and $\sim$2700 from 1-5 μm. NIRSpec has two 2Kx2K HgCdTe detector arrays in the focal plane built by Rockwell Science Center and a fully programmable field selector in the form of an array of small shutters (microshutters). The European Space Agency (ESA), will deliver the instrument with detectors and the field selector, a fully programmable two dimensional MEMS aperture mask, coming from NASA/Goddard Space Flight Center (GSFC). A complete description of JWST, its mission, and scientific objectives is given in Gardner et al.[1] Details of the NIRSpec design and its capabilities can be found in Posselt et al.[2] Figure 1 shows an artist's concept of the NIRSpec instrument.

A large field of view MOS provides a highly efficient means of simultaneously surveying the spectral properties of multiple objects. To achieve this goal, the spectrographs require a field selection device to isolate the objects of interest from the surrounding objects and sky background. Ground-based spectrographs have provided field selection by a variety of methods– customized aperture plates have been drilled for each object of interest[3] and fiber optic robots[4] have been designed to accurately position fibers to collect the light from only target objects. However, drilled aperture plates and the

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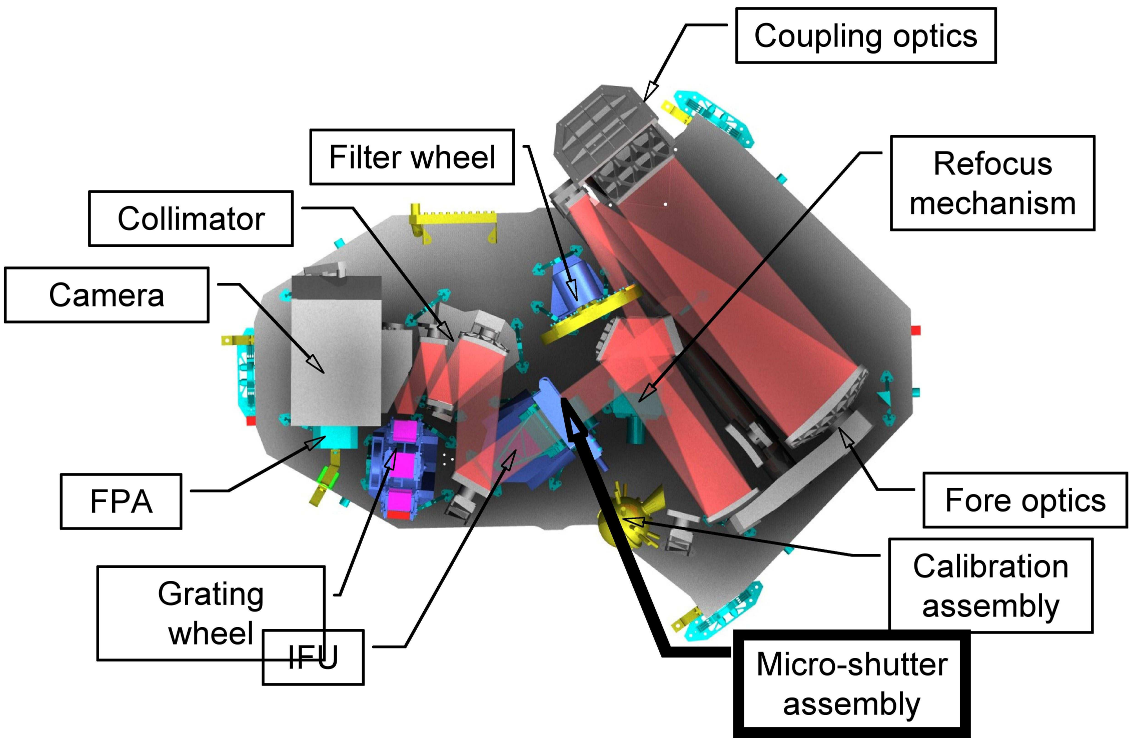

Figure 1. Artist's Concept of the NIRSpec Instrument from Posselt et al.[2] The location of the microshutter subsystem is shown by the heavy line.

mechanically complex and massive fiber robots are impractical for use in the space flight environment. Here we describe the development and current status of a fully programmable 2-dimensional array of microshutters. This MicroShutter Subsystem (MSS) is to be used as the field selector for NIRSpec. In this particular implementation of the technology, the devices are designed for use at near infrared wavelengths in a space-borne application, however, similar devices may be useful in other applications where their compact size, low power requirements, and great flexibility may enable enhanced performance. In the following sections, we discuss the motivation for using microshutters in this instrument, their design, characteristics, fabrication methods, testing and progress toward delivery of flight-qualified devices and an entire field selection subsystem.

2. DESIGN OF MICROSHUTTER ARRAY

2.1 Requirements

NIRSpec's field of view is designed to be large enough for there to be large numbers of high redshift galaxies at each JWST pointing. To meet its scientific requirements, NIRSpec must determine the spectra of many ($\sim$100) galaxies simultaneously in each field of view. The aperture mask that selects the objects to be studied must provide high transmission in the region of the objects selected for study and be highly efficient in blocking the light from masked off regions– high contrast– to avoid contaminating spectra with data from foreground objects . In addition, the presence of the field selector should not greatly reduce the sky coverage in the field of view – apertures should have a high filling factor in the focal plane. The device must also be fully addressable, withstand the rigors of launch and perform in the space flight environment. We summarize the requirements in Table 1.

2.2 Microshutter Array Construction

A unit cell for a microshutter is shown in Fig. 2. The microshutter is suspended via a torsion bar hinge, which acts like a torsion spring. The microshutter blade is fabricated on 0.5μm thick high strength material and its static position is in

Table 1. Microshutter design requirements.

Microshutter Quadrant Format	171x365
Microshutter System Format	342x730
Unit Cell Size	$\sim$100 μm x $\sim$200 μm
Contrast Ratio	$>$2000 ($>$10000 goal)
Addressing	Random
Required lifetime	$>3.9\text{x}10^4$ cycles
Operating Environment	Vacuum
Operating Temperature	$\sim$ 35K
Full Subsystem Mass	$\leq$10 Kg
Average Power	40 mW

the plane of the "front" side of the microshutter array (MSA) as seen in the figure 2. The microshutter blade surface is coated with thin stripes of CoFe ($\sim$90% Iron and 10% Cobalt) to provide high magnetic permeability to the microshutter blades for actuation, the process of moving them to their latched position. This magnetic material is required for proper operation of the addressing scheme which we describe in section 2.3. In addition, the microshutter blades are covered with a thin layer of electrically conductive material, a metal nitride. This material serves three purposes; 1) to block passage of light through the very thin silicon nitride microshutter blades when they are closed and 2) provide electrical contact for addressing and 3) to improve flatness at cryogenic temperatures. The flatness requirements are discussed below.

A light shield surrounds the "front" side of each microshutter blade (see fig. 3) that blocks the passage of light around the microshutter when the microshutter blade is in the closed position. The entire array of microshutters is supported by the thick ($\sim$120 μm) silicon "egg crate" structure (fig. 4).

The NIRSpec requirements call for a field of view of about 3.6$'$x 3.6$'$. The microshutter subsystem must cover this area with 342 microshutters in the imaging direction and 730 microshutters in the spectral dispersion direction. With the

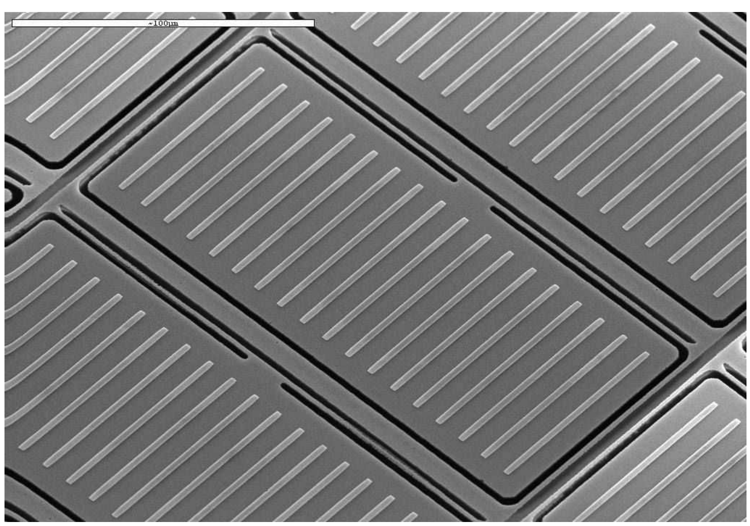

Figure 2. SEM Image of microshutter. The figure shows an SEM image of a portion of a wafer during processing. At this stage of processing there is no light shield so the microshutter blade is visible. The torsion hinge can be seen as well as the CoFe stripes that give the microshutter blades their magnetic susceptibility. Light shields, fabricated later in the processing, will cover all gaps around the periphery of the rectangular microshutter blade so high contrast can be achieved.

plate scale in the NIRSpec, this corresponds to a physical region approximately 75 mm on a side. In addition, the MSS layout must provide space for some fixed apertures. To satisfy this requirement, the flight MSS will be assembled from four sub-array assemblies, each of which contains a MSA in a 171x365 configuration.

The fabrication of microshutter arrays is done using silicon micromachining techniques in the GSFC Detector Development Laboratory. Silicon nitride was found to be the material of choice for the microshutters due to its superior strength and excellent mechanical and thermo-mechanical properties. Using this material, the microshutter blade is removed entirely from the optical path by a rotation of 90°. In testing of early material samples, this large rotation has been repeated up to 10^9 times before signs of fatigue appeared. This is well beyond the requirements needed for the NIRSpec planned in orbit operations.

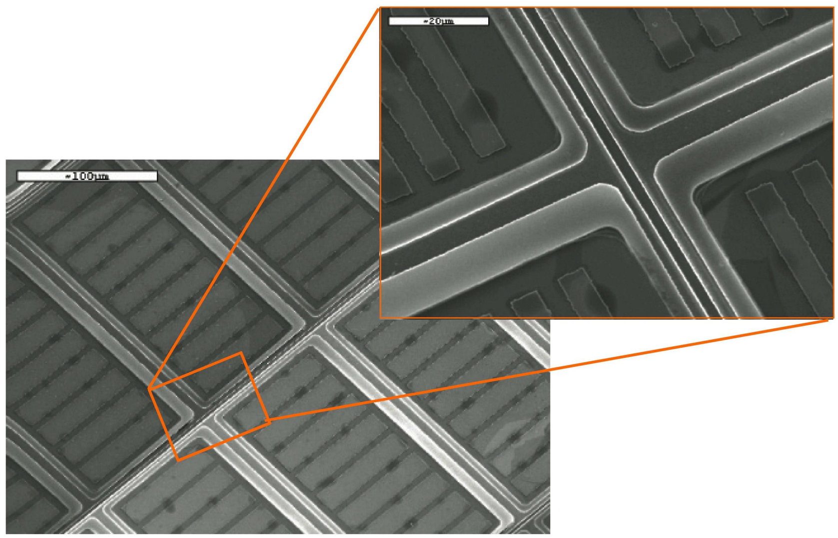

Figure 3. Front side of a MSA. The figure shows two images of the front side of an array. The inset shows the details of the light shields.

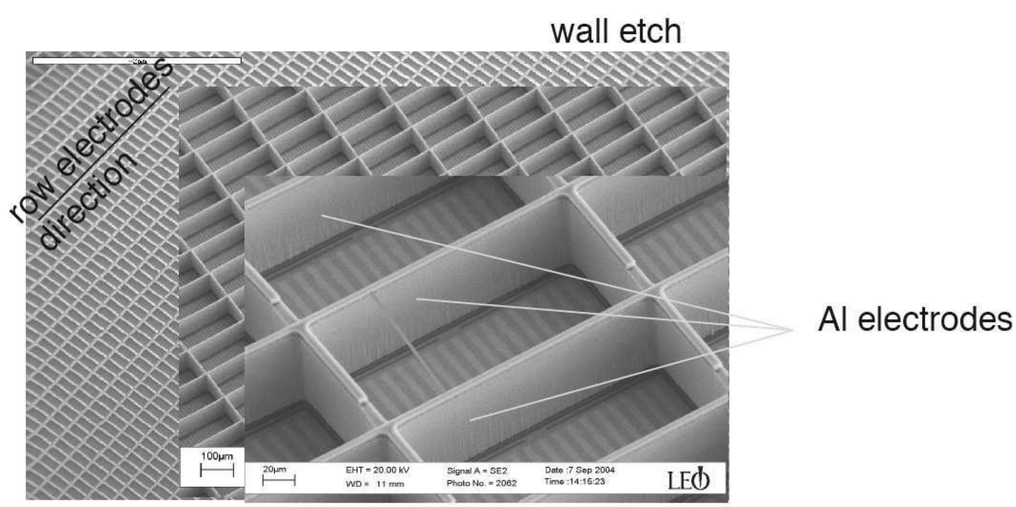

Figure 4. Back side of a MSA. The figure shows three images of the backside of an array, each at greater magnification. At the highest magnification the details of the individual shutters and their construction can be seen.

Micromirror MEMS devices have stringent flatness requirements because they are used in reflection. For a microshutter device, these requirements are more relaxed, but significant deviations from flatness or tilting of the microshutter blades can compromise the ability of the microshutter to close properly and dramatically reduce contrast. Although some deviation from flatness can be tolerated at room temperature, a tighter specification ($\sim$2 μm) is required at the operating temperature of $\sim$35K. To help meet the flatness requirements at low temperatures, the thickness of the metal nitride used for the microshutter blade electrical contacts is carefully controlled so a balance between the metal nitride film stress and the silicon nitride stress can be achieved. The results is a microshutter blade that is slightly bowed at room temperature, but becomes nearly flat at 35K.

The microshutters are controlled by a cross addressing scheme (see section 2.3). This technique is used because it requires no active electronics in the unit cell and all addressing electronics is external to the MSA chip. Having no on-chip electronics leads to simpler fabrication procedures. With no unit cell electronics to hide, the microshutter blades can occupy a large fraction of the unit cell area, allowing higher fill factor for the array. The cross addressing technique requires deposition of electrodes connected to the vertical walls on the torsion hinge side of each unit cell where the microshutter blades can be latched. The metal nitride coating on the microshutter blades themselves provides the electrode for the blades. Aluminum is used for the vertical wall electrodes and is deposited by angle deposition.

To stop the light leaking through the gaps between each microshutter blade and the surrounding silicon support structure and torsion hinge , an aluminum light shield is fabricated which overhangs the gaps. A larger overhang will improve contrast, but results in lower filling factor due to the larger area that the light shield occupies around the edges of each unit cell. A more complete description of the development, fabrication, and integration of microshutter arrays can be found in Li et al.[5]

2.3 Operation

The microshutters arrays are magnetically actuated, electrically addressed and electrostatically latched. Early tests showed that while purely electrostatic actuation might be possible, unacceptably high voltages were required and are not practical in the space environment. Instead a magnetic actuation combined with electrostatic latching is used. A narrow strong quadrupole magnet is swept across the array; in synchronism with the sweep, electrical signals are applied to the microshutter blades and to the vertical walls to cause all the microshutters to open. On the return sweep of the magnet, the desired pattern of open/closed shutters is achieved by allowing shutters to close will leaving open ones in the desired configuration to remain open. Figure 5 shows a schematic depiction of the array configuration process. In practice, the microshutter release electronics signals are also synchronized with magnet position as it returns to its home position. Because released shutters are captured by the magnetic field, they approach their light shields gently rather than with all the momentum created by the torsion hinge force. This technique avoids the microshutter blades slapping into the light shields each time a microshutter blade is released. This synchronized release technique greatly improves MSA lifetime.

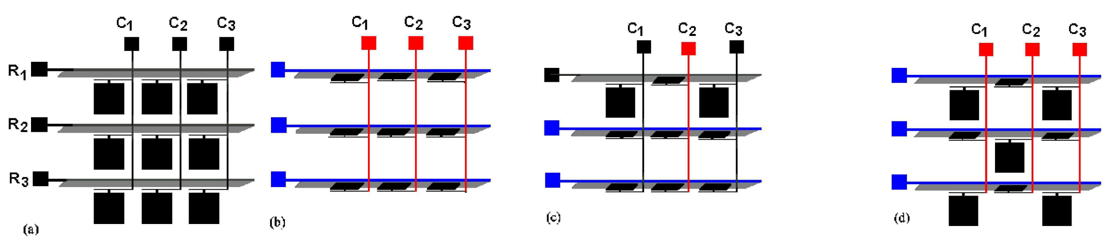

Figure 5. Cartoon showing the configuring of a MSA. The diagram shows the sequence required to configure the array to an arbitrary pattern of open/closed shutters. a) All the shutters are in their static closed position at the outset. b)Voltages are applied to all rows and all columns and the magnet sweeps across the array and forces the shutters close to the sidewall. Because voltages of opposite polarity are present on the sidewall and the microshutter blade, a strong electrostatic force results and the microshutter blades all latch electrostatically resulting in a fully open array. c) Next, the voltage on the columns in the row that is being configured is set to zero and the voltages on the column in that row that are to be closed are turned off. Microshutters that were open continue to be held open by the column voltage alone and microshutters that are to be closed release from the side wall because there is neither voltage on the sidewall nor microshutter blade electrodes. d) After cycling through all the rows, the desired configuration is achieved.

2.4 Packaging

Once the 171x365 MSA chips are fabricated, they must be integrated into the MSA quadrant assembly. This assembly combines the control electronics with the MSA chip and provides positional reference and mounting points for mechanical and optical alignment of the assembly (see Fig. 6. Four of the quadrants must be mounted in a 2x2 mosaic to produce the full Microshutter Subsystem (MSS). This layout of the MSS is shown schematically on the right side of fig. 6. Note that the NIRSpec focal plane contains several fixed slits and an aperture for the integral field unit (IFU). This MSS design offers some flexibility as each MSA quadrant is manufactured and tested independently before integration into the MSS.

The MSA chips are mounted on quadrant substrates and are made from 2mm thick single crystal silicon. Since this silicon material is the same as the 120 μm thick support structure in the microshutter chip, there are minimal thermal stresses when the unit is cooled to the operating temperature of $\sim$35K. A clear aperture is cut in the quadrant substrate where the MSA chip will be mounted. There are more than 1000 electrical connections around the periphery of this aperture for making the required electrical contacts to the MSA chip. These connections are made with both bump bonding and wire bonding techniques. The MSA quadrant assembly also contains the electronic chips and other required connectors used for control and monitoring of the MSA quadrant assembly.

2.5 Electronics

The electronics on the MSA quadrant assembly consists of five high voltage 128-channel serial to parallel converters and shift registers. These devices each contain four 32 bit shift registers and are customized radiation-hardened versions of a commercial device manufactured by Supertex Inc. In this application they must operate at the focal plane temperature of $\sim$35 K. These devices are controlled by external electronics operating at a higher temperature. The entire microshutter package including the magnet transport mechanism must operate with an average power of less then 40 mW.

2.6 Optical Performance

Microshutters in the array must meet critical optical performance requirements. These include high transmission for open microshutters to let in as much light as possible from the faint objects being studied and very low transmission at closed microshutters to block out the light of the sky and any bright foreground objects in the large field of view of NIRSpec. Significant light leakage through closed microshutters results in excess photon noise from the background light and possible contamination of the spectrum of the selected object.

Transmission losses are primarily set by the unit cell design and diffraction effects. As long as the microshutter blade is latched to the vertical wall and is totally behind the light shield, there is the inevitable geometrical loss due to the area of the unit cell blocked by the light shield. For the devices discussed here, the filling factor due to the design geometry is $\sim$67%. Diffraction losses are, of course, wavelength dependent.

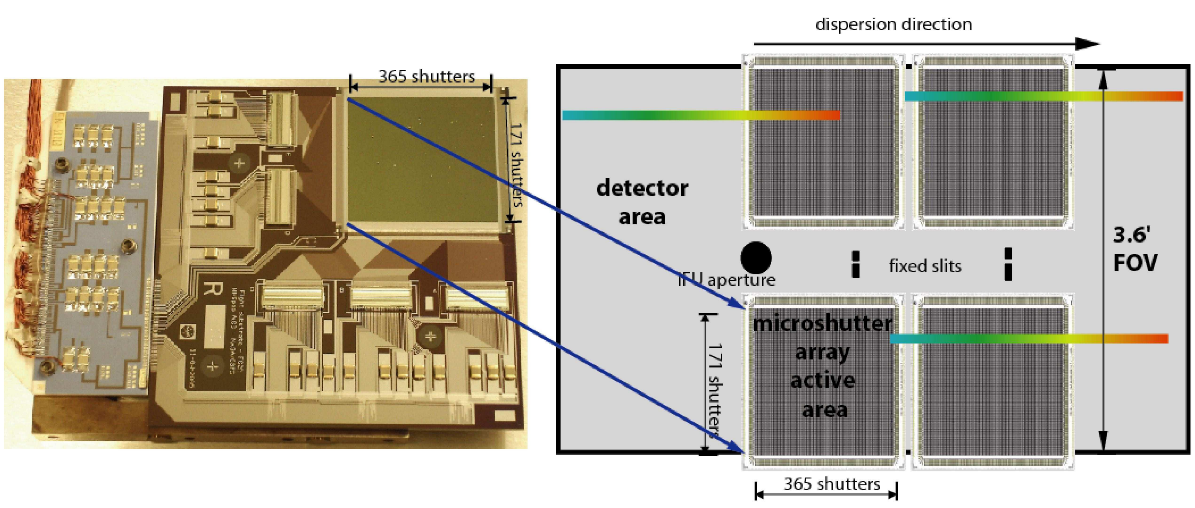

Figure 6. Fully Assembled MSA Quadrant. At the left side of the figure there is a picture of a fully assembled quadrant. The microshutter array is in the upper right. Around the periphery are the electronics. On the right side of the figure the optical locations of the four MSA quadrants are shown relative to the detector array. The locations of the IFU aperture and the fixed slits are also shown.

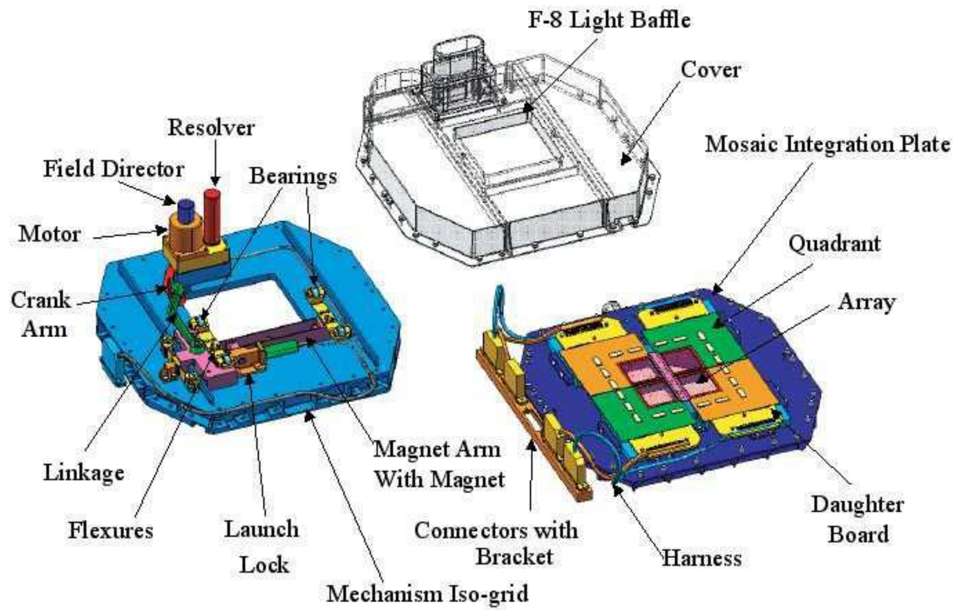

Figure 7. Artist's Concept of the Entire Microshutter Subsystem. The integration of the four quadrant assemblies can be seen in the lower right of the figure. On the left, is the magnet transport mechanism. A single magnet is used for all four quadrants.

Since the microshutters are designed to move against the sidewalls, they should be hidden under the light shields when they are latched to the walls. Thus the transmission characteristics are primarily set by the light shield design and the wall thickness in the microshutter array chip.

For JWST purposes, contrast is the ratio of the power at the detector with light coming through the microshutter aperture when open to the power at the detector when the microshutter blade is in the closed position. The leakage through the microshutter when it is closed is primarily determined by the flatness of the microshutter, the light shield design and the wavelength of the light. Our tests have shown that a high contrast closure can be achieved as long as the gap between the microshutter blade and the light shield does not exceed a few microns. A detailed discussion of the optical performance, modelling of the light leakage and testing of the microshutters is given in Kutyrev et al.[6]

2.7 MSS Integration

The MSA quadrants must be integrated into the MSS. In addition to the four MSA quadrants in correct optical locations (see fig.7), this configuration contains the magnet transport assembly and light baffles. The MSS mount also contains provision for proper optical alignment in NIRSpec. Electronics for magnet transport control is not contained in the MSS, but in external microshutter control electronics.

2.8 Flight Qualification

Prototype MSAs were subjected to the rigors of launch and space flight-like conditions. Prototype MSA quadrant assemblies were subjected to acoustic and vibrational testing at qualification levels relevant to the JWST's Arianne launch vehicle. In addition to those tests, a prototype array was subjected to life testing as it accumulated 100,000 cycles– approximately 2.5 times the NIRSpec requirement. Electronic components on the quadrant assembly were subjected to $\sim$ 60-100 krad of ionizing radiation from a Co^{60} gamma ray source. Although the MEMS microshutter devices were not expected to be particularly sensitive to ionizing radiation, a MSA was also tested using the gamma ray source.

A microshutter that fails in the open configuration is a more serious problem than a microshutter that fails in the closed configuration. An open microshutter in a row means that some light will fall on the detector from that open microshutter and contaminate the spectrum of the intended object. Because most NIRSpec sources are very faint galaxies, this contamination is troublesome. A row with a single failed open microshutter may not permit NIRSpec to perform up to its full requirement on a object in that row. On the other hand, a microshutter that is failed closed cannot be used for an object at that position;

since NIRSpec is generally in a source-rich environment, the loss of an opportunity to observe a few objects due to failed closed microshutters has little overall impact on achieving the scientific objectives. Because of this situation, acceptable MSAs can have up to 3% failed closed microshutters at the beginning of their life (BOL) but no more than 3% of the rows may have one or more failed open microshutters. At the end of life, up to 20% of the microshutters may fail closed, but only 6% of the rows may have one or more failed open microshutters. In our testing to date, we have not experienced such a high rate of failures of either type.

2.9 Summary

Large scale two dimensional arrays of MEMS-based microshutters have been developed. These fully addressable devices are simpler, less massive, and lower power than some current methods for field selection used in ground-based applications. The devices are magnetically actuated, electrically addressed and electrostatically latched. Some of the prototype devices we are currently fabricating, assembling and integrating into fully functional assemblies have been subjected to acoustic, vibrational and environmental conditions simulating the rigors of launch and operation in space. Lifetime testing has shown that the devices can meet NIRSpec requirements. At the conclusion of these tests the devices continued to meet specifications. We expect that a completed MSS will be provided to ESA for use in NIRSpec.

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The development of these MEMS represents the work of a great many colleagues and support staff at the Goddard Space Flight Center over many years. We greatly appreciate their efforts in bringing the microshutter project to its current state of readiness. The microshutter effort is supported by the European Space Agency which is responsible for the NIRSpec instrument.

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