Microshutter Arrays: High Contrast Programmable Field Masks for JWST NIRSpec.

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ABSTRACT

Microshutter arrays are one of the novel technologies developed for the James Webb Space Telescope (JWST). It will allow Near Infrared Spectrometer (NIRSpec) to acquire spectra of hundreds of objects simultaneously therefore increasing its efficiency tremendously. We have developed these programmable arrays that are based on Micro-Electro Mechanical Structures (MEMS) technology. The arrays are 2D addressable masks that can operate in cryogenic environment of JWST. Since the primary JWST science requires acquisition of spectra of extremely faint objects, it is important to provide very high contrast of the open to closed shutters. This high contrast is necessary to eliminate any possible contamination and confusion in the acquired spectra by unwanted objects. We have developed and built a test system for the microshutter array functional and optical characterization. This system is capable of measuring the contrast of the mciroshutter array both in visible and infrared light of the NIRSpec wavelength range while the arrays are in their working cryogenic environment. We have measured contrast ratio of several microshutter arrays and demonstrated that they satisfy and in many cases far exceed the NIRSpec contrast requirement value of 2000.

Keywords: microshutters, micro-optics, spatial light modulator, programmable aperture masks, micromirror arrays, planar structures

1. INTRODUCTION.

We are developing a programmable transmissive field selector for the James Webb Space Telescope Near-Infrared Spectrometer. A primary goal for *JWST* is to detect the first galaxies to form in the universe, and then to follow their evolution and the growth of structure.[1, 2] Large scale redshift surveys are essential tools to allow us to identify these first galaxies, and to follow the subsequent development of structure. High redshift galaxy candidates will be sparse on the sky even with *JWST*, so a multi-object spectrometer is essential to provide the most capable tool for this study of the early universe.[3]

Field selectors can be realized in a variety of ways. Perhaps the most common way for multiple object selection in astronomy nowadays is a multiple fiber spectrograph. It allows a flexibility of positioning of each individual fiber exactly on the object and also has an advantage of best possible way of packing spectra on the detector. These mechanisms are limited in the number of fibers that can be positioned. Building an instrument that would have a fiber selector based spectrograph with the mass, volume and cryogenic limitations makes it virtually impossible. An appealing alternative to this approach is a multiple mirror devices[4–6] that are widely used in projectors and readily available commercially. However, these devices are non cryogenic and building a cryogenic version requires significant efforts, essentially developing the device specifically for that application. Though it is hard enough technologically to build a micro-mirror device that would perform a required object selection task, it is not technological challenges that reduce the usefulleness of such a device in astrophysics spectroscopy. The maximum contrast ratio that achieved by the micro-mirror device is inherently limited by the diffraction on edges and scattering on the surface.

We took an alternative to micromirrors approach to the problem[7] and pursuing a goal of creating large fully addressable microshutter arrays of small elements (100μm typical dimension) with high area coverage efficiency (60% or better for the ratio of shutter area to the total area). Although advantages of the shutters for applications requiring high-contrast imaging are obvious, there have been no large array microshutters developed

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so far. From the optics point of view, transmissive masks are far better than reflective devices, in part because of much lower diffracted and scattered light, which is one of the most important parameter in faint objects spectroscopy. However, microshutters unlike micromirrors require large angles of rotation of the individual microelements, making the implementation very challenging compared to the micromirrors. In micromirror arrays the area behind the mirrors is available for the structures providing actuation and addressing, whereas in the microshutter design all these should be hidden in tiny support structures between the microshutter blades and/or on the blades themselves. Despite all these challenges, we have designed and built microshutter arrays that satisfy the *NIRSpec* requirements

Microshutter device (ultimately comprised of four microshutter arrays) should allow random access addressing for 200 or more objects targeted simultaneously. According to the *NIRSpec* requiremenets the contrast provided by the microshutters should be at least 2000 or better (10,000 is a goal). The device should operate for ten years and with a lifetime of 3.9×10^4 cycles with minimal failures at the cryogenic environment of the $JWST$at temperatures around 35 K. It also must meet power dissipation requirements of 40 mW average at 35 K and survive total life radiation dose of 48 kRad. In this paper we describe the basic principles of the microshutter design and operation and optical testing and performance of the microshutter arrays.

2. MICROSHUTTER ARRAY DESIGN AND PRINCIPLES OF OPERATION.

The basic concept of the microshutter is illustrated in Fig. 1. The microshutter array is fabricated from a thin silicon nitride membrane. Each shutter is a square or rectangular blade that is suspended on a torsion bar etched from the same membrane. This torsion bar acts like a torsion spring that is strong enough to hold the shutter flat and yet the stresses developed in it are low for a multiple operation (rotation up to 90 °) without any noticable risk of breaking the torsion bar. The initial idea of the microshutter design came from the previous works at Goddard Space Flight Center (GSFC)[8] on the bolometer arrays. These pop-up bolometers are mounted on very thin flexible silicon "legs" bent to 90° from the detector plane. In this project we have expanded this idea further, making the flexible suspension of the shutters in the form of the torsion beam.[9] Each shutter unit cell covers an area of $\approx 100\mu$mx200 μm and is connected to a frame through a neck region and a torsion beam. This design allows to have longer torsion bar and therefore reduces the stresses in the material. The initial design of the micrsohutter shown Fig. 1 had square 100 μm x100 μm microshutters. It was later changed to 100 μm x 200 μm to accommodate changing science requirements on sampling in spectral and imaging directions.

The initial studies of the microshutter concept were carried out using focus ion beam milling machine at the University of Maryland[10, 11] It was a very important stage of the project when in a short time we were able to prove the concept, conduct initial device reliability test and lay out the path on the possible device design, its properties and limitations. The following stages of the project were carried out in-house in the Detecor Development Laboratory at GSFC with microlithography and Deep Reactive Ion Etching (DRIE) process as an enabling technology for this project.

The $JWST$ *NIRSpec* requirements define the microshutter system design layout. The primary defining requirements are large array dimension, high efficiency transmission and low light leakage in closed position. Individual pixels of the device should be tightly packed with very small relative size of the interstitials and there should be no gaps in the shutter structure in the closed position, thus eliminating any path for light leak.

Microshutter arrays are fabricated from SOI wafers using DRIE process. Fabrication process includes mutliple steps to produce a device that has all the elements that required for actuation and addressing and satisfies optical performance requirements. A number of steps required to produce all the components of the array, including torsion bars, microshutter blades, support grid, light shields and all the required electrodes and insulation layers. One of the most important parts of the design and the fabrication that has been developed in this project is lightshields. These aluminum cantilevered light shields cover the cuts in the silicon nitride that define the shutter and hinge prevent light from leaking and scattering through the gaps between the shutters and the frame structure (Fig. 2, 3)

The actuation and selection of shutters in such a densely packed array is a challenging problem. To assure high effective open area, the spaces between the shutters must be made as small as possible, leaving little room for actuation mechanisms and/or selection electronics. We have explored a number of different approaches for

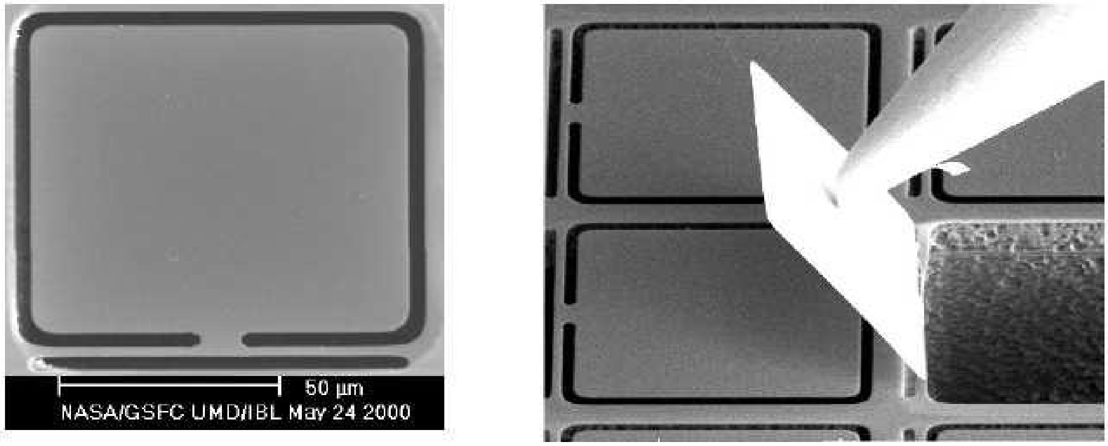


Figure 1. SEM image of a silicon nitride mechanical microshutter (a) and a shutter opened using a probe (b).

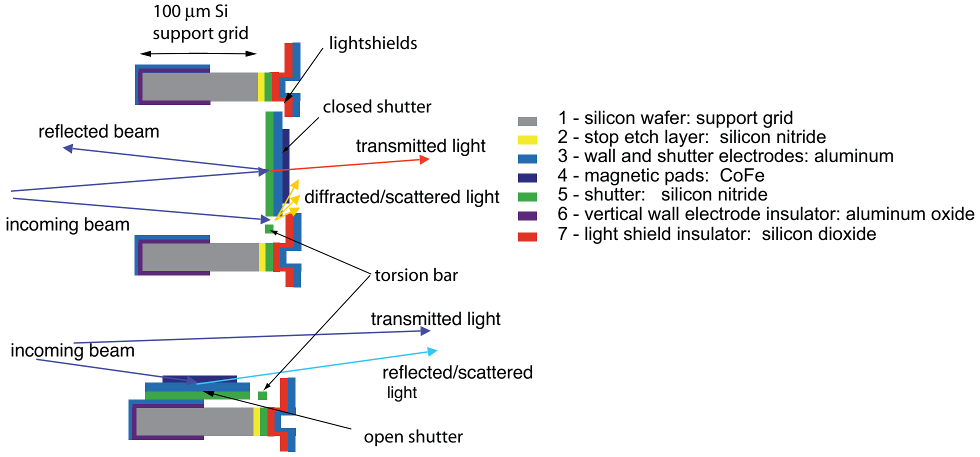
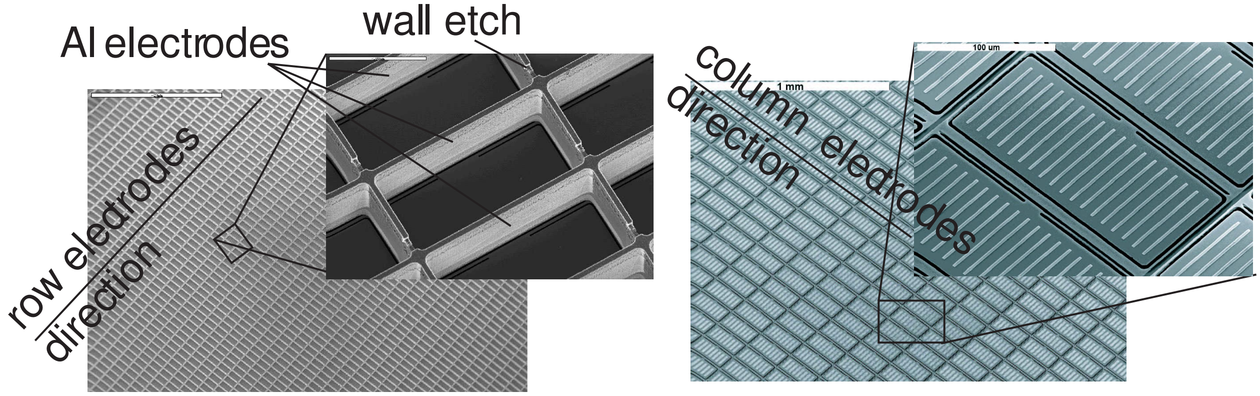


Figure 2. A cross section diagram of the microshutter array. Two cells are shown on the diagram: one with the microshutter closed (top) and another one with the microshutter in open position. The shutters are etched out of a silicon nitride membrane $0.5\mu m$ thick, mounted on top of a $100\mu m$ microns thick silicon wafer. One of the crucial parts of the microshutter array design is Al light shields that prevent light leaks through the gaps between microshutter and the walls. Legend: 1– support grid: silicon wafer, 2 – stop etch layer: silicon nitride, 3 – wall and shutter electrodes: aluminum, 4 – magnetic pads: CoFe, 5 – shutter: silicon nitride, 6 – vertical wall electrode insulator: aluminum oxide, 7 – light shield insulator: silicon dioxide.

actuation with extensive prototyping of the devices.[12] One of the most obvious and attractive is an electrostatic actuation. Our analytic models and tests of the electrostatically actuated shutters demonstrated that the voltages required to rotate the shutters to nearly 90 degrees out of the plane are in the range of hundreds of volts depending on the thickness and geometry of the torsion bar. It is prohibitively high since it makes the fabrication of the insulation between the electrodes virtually impossible and it also creates problems with sparking and electric discharge in vacuum on the sharp corners. The result of our development is a hybrid magneto-electrostatic actuation and addressing mechanism. It involves magnetic actuation and electrostatic latching and addressing.[13,14]

The shutters are coated with a high permeability soft magnetic material CoFe ($\sim$ 90%Fe and 10% Co). CoFe is a soft magnetic material with low residual magnetization. Its advantage is in a high permeability, which reduces the magnetic field required to rotate the shutters. To actuate the shutters we use specially designed quadrupole



a)

b)

Figure 3. a) Aluminum back electrodes deposited on the walls of the microshutter support grid at 45 degrees angle to provide good area coverage on the walls and electrical continuity along the rows. Small dips are etched out to insulate the adjacent rows. The deposition is done at 45 degrees to produce a coating on only one side of the wall. b) SEM image of the front of the shutters with the light shields and column electrodes. The light shields prevent leakage of the light through the gaps between the shutters and the support structure. Column electrodes are orthogonal to the row electrodes on the back walls to enable cross addressing scheme of the shutter array.

magnet (Fig. 4). The magnet is scanned below the shutter array rotating the shutters out of the plane and bringing them in the proximity of the wall electrode (Fig. 3,4). During the magnet scan all the front and the back electrodes have +V voltage applied to them and back electrodes are at -V. The voltages are selected high enough to capture shutters electrostatically and keep them attracted to the walls as the magnet passes by. As a result, after the magnet completed the scan across the array, all the shutter are held electrostatically attracted to the walls in the open position. The voltage V is chosen so that a potential difference of V is sufficient to hold the shutter open, once captured. The latch (capture) voltage is higher and 2×V voltage is set to provide reliable latching of the shutters to the walls.

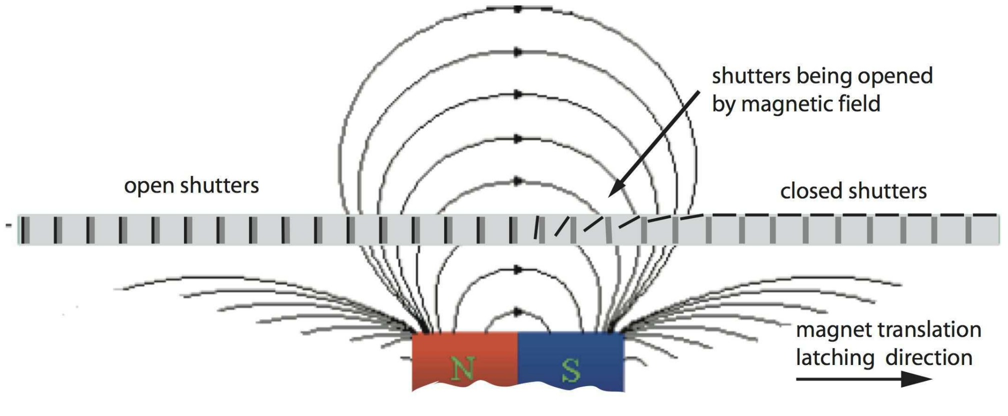


Figure 4. Microshutter actuation: the array and magnet in cross-section in the process of actuation and latching. The permanent quadrupole magnet scans cross the array rotating the shutters out of the plane and thus bringing them close to the walls. Latching voltage applied between the shutters and walls holds them open after the magnet passes. Once the magnet scanned the whole array all the shutters are latched.

Subsequently, when we ground a given row on the array, all shutters on that row which have -V applied to their columns will remain open. Only those shutters where both the row and the column are grounded, will close. This addressing scheme, which we call cross addressing, provides shutter selection without requiring any active electronics on the array, significantly simplifying the design and fabrication. There are only electrical connections to columns of shutters and rows of vertical electrodes. To bring electrical connections from the microshutter array rows and columns it is mounted on a square silicon insert board, which is in turn, mounted on a printed circuit board. An image of the large format array closed, open and with 2D addressing pattern is presented in Fig. 5.

a)

b)

c)

Figure 5. *NIRSpec* design array 171 × 365 shutters: a) all shutters are closed, b) all shutters are actuated and latched, c) Array addressed with "Maryland blue crab" pattern. The image is acquired in transmitted light, so that open shutters appear bright and closed shutters are dark.

3. MICROSHUTTER ARRAY PERFORMANCE.

The evaluation of a microshutter must establish; 1) proper electrical function, no shorts or opens. 2) proper mechanical function of shutters. 3) the ability to latch shutters. 4) the ability to deselect (address) shutters and create a desired pattern. The electrical tests are carried out at many steps in the production process, at the completion of processing, and after bonding to the carrier chip. Mechanical function of the shutters is evaluated at the completion of processing prior to mounting by rotating the shutter in a strong magnetic field for testing of mechanical actuation without latching. After mounting on the carrier board, it can be tested with the magnet in the test cryostat. In this facility, we can also test our ability to latch and to address the shutters (Fig. 6).

One of the most important aspects of the array performance is reliability and maximum number of actuations that shutters can withstand before failure. An extensive program on material studies and failure analysis has been carried out. The results of that study confirmed that shutters do not fail until a very large number of actuations, far exceeding *JWST* requirements.[15] At the beginning of life, there can be permanently open shutters in at most 1% of the rows, and less than 5% of the shutters can be permanently closed. At the end of life, less than 5% of the rows can have a permanently open shutter, while 20% of the array may be permanently closed. The much more stringent requirement on the open failures is due to the fact that the grating will disperse light from a permanently open shutter over much of an entire row of detectors along the dispersion direction, significantly reducing their utility. These operability requirements are stringent, and impose significant fabrication and testing requirements. Tests of arrays fabricated during the process development have been obtained which suggest that significant infant mortality of shutters may occur.[16] After the initial limited life test is completed, all failed open shutters are patched using custom developed process of bonding small pieces of silicon wafer on top of the failed open shutters thus eliminating all the gross light leaks through the array.

To assess the actual performance of the shutter arrays we have designed and built a microshutter functional and optical test facility. This facility allows to subject the arrays to repeated actuation and latching process at accelerated rate. The actuation, latching and addressing is done in exactly the same manner it will be done on the real real flight device. All the shutters are latched on every cycle of the magnet passes by the shutter

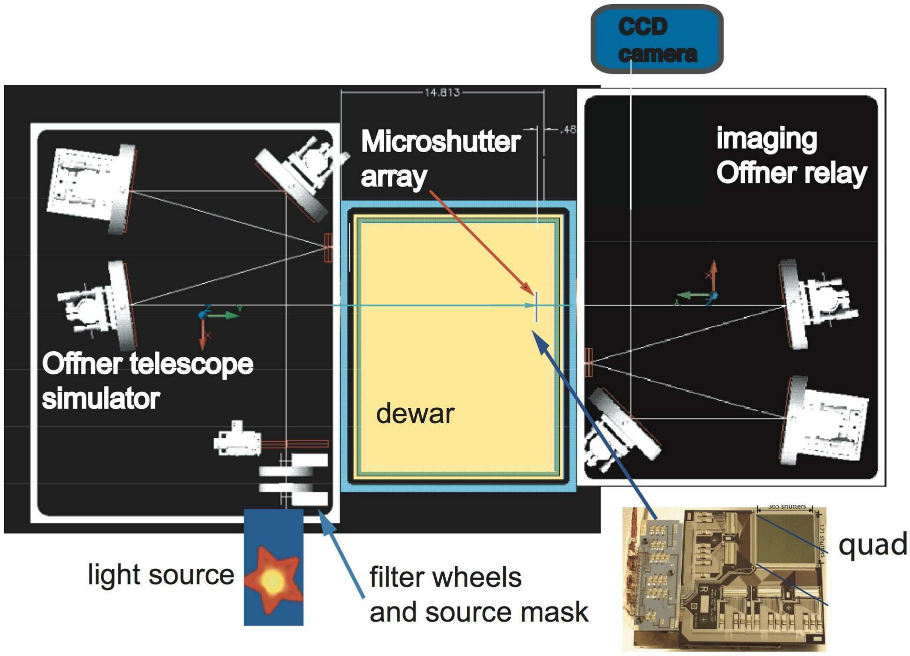


Figure 6. Microhsutter array optical test layout: telescope simulator on the left, microshutter array dewar in the middle and imaging optics with CCD camera on the right. All optics is reflective except for the dewar windows and demagnifying lens (not shown) located in front of the CCD imaging camera. A microshutter array mounted on the silicon quad is shown in the lower right corner. The quad electronics allows high voltage latching and addressing of the array. It is mounted in the dewar along with the magnet transport mechanism. This setup allows to perform full functionality, life and optical testing of the flight mciroshutter arrays. Microshutter array quad assembly is shown in the lower right corner.

array. The magnet can be moved at up to 0.5Hz cycling frequency, which allows to complete a few thousand of actuations to carry out the life test within a few hours of continuous operation. The flight like microshutter arrays mounted on silicon quads were tested for actuation, latching, addressing and for life operation. There were no microshutter torsion bars failure observed in these tests due to the torsion bar breakage. Primary mode of the failed open shutters was due to stiction or irregularities in fabrication of the light shields or the shutters themselves.

Besides the basic functionality of the array in terms of actuation, latching and addressing, microshutter must satisfy optical requirements.[17] The most important optical parameter of the microshutter array is the contrast. *JWST* requirements define contrast for the microshutter array as the ratio of incident power reaching the detector with all of the shutters open to that reaching the detector with the shutters closed. The magnitude of any leakage through the device is the inverse of the contrast. Efficiency is defined as the percentage of the focal plane beam power that reaches the detector when the shutters are open divided by the power that would reach the detector with the ideal open slit of the size equivalent to the slit formed by the open shutters. To achieve the best possible performance the walls are made as thin as possible and the gaps between the shutters and the frame are made as small as technologically possible to provide maximum geometrical fill factor and lowest light leakage in the gaps.

To determine the transmission and contrast provided by the microshutter array we used a large area source with uniform illumination on multiple shutter. To measure efficiency a reference image of the source with the shutter array completely removed from the optical path is acquired. Efficiency is calculated as a ratio of flux detected with the shutters open to the total flux detected with the shutters removed from the beam. Our optical tests demonstrated $\approx 60\%$ transmisson (consistent with the geometrical fill factor) and about 300 contrast ratio for the microshutter arrays without the light shields. Some light leakage occurs through the gaps between the shutter blades and the frame structure and the contrast does not satisfy the requirement. With the lightshields

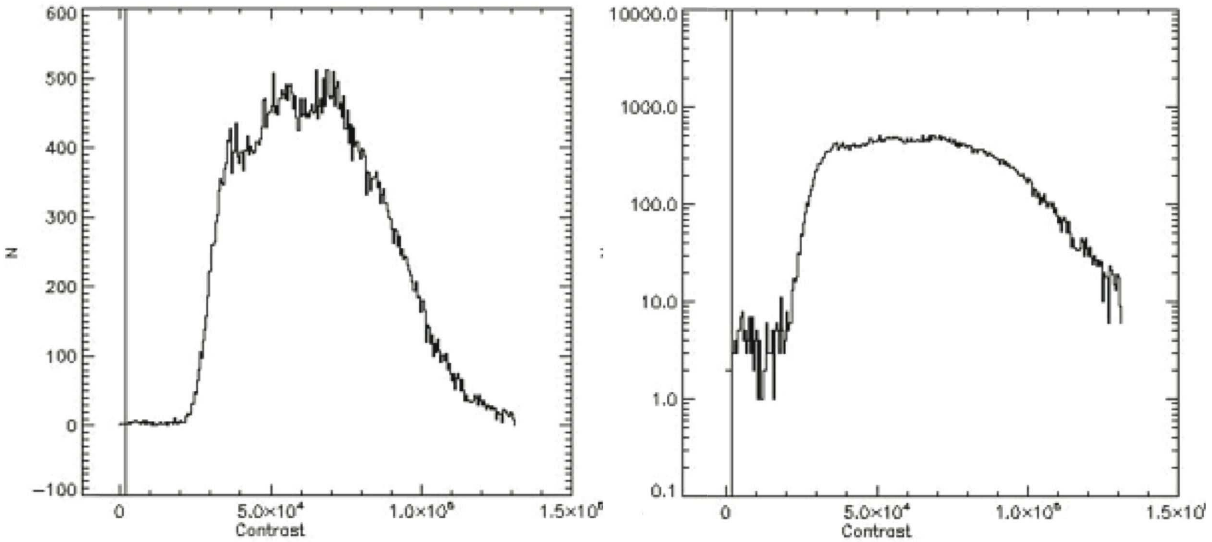


Figure 7. Histogram (linear scale on the left, logarithmic on the right) of the contrast distribution of the flight quality microshuter array (counting individual shutters). Majority of the shutters show very high contrast with the average value of about 66 thousand. A vertical line denotes *NIRSpec* 2000 contrast requirement. The distribution is characterized by a sharp cutoff on the lower contrast values with only a handful of shutters with the contrast lower than (10^4, *NIRSpec* requirements goal).

added to the shutter array the light leakage is reduced to a level that far exceeds minimal requirements on the contrast produced by the shutter arrays. These results demonstrate that the design of the shutters with the lightshield can provide the required transmission and contrast ratio.

The optical test setup for the micro-shutter assembly was designed to evaluate various optical characteristics of these devices. It is designed to simulate the beam of the near infrared spectrometer at the location of the microshutter array system in the *NIRSpec* optical bench. The test setup is capable of carrying the contrast measurements over the *NIRSpec* wavelength range (0.5μm to 5 μm). The optical system is build using reflective design built from two identical Offner relays: one for simulating the source and another one for imaging shutter array onto the detector. The only refractive element employed in the system is the demagnifier lens, the last component in front of the CCD camera that that allows the full microshutter array image to fit onto the CCD detector.

The telescope simulator proves a beam that simulates the *JWST*beam (left side of the Fig. 6). To simulate *JWST* optical path and parameterize the effects of entrance pupil, wavelength and exit pupil, the optical setup has a number of field stops and equipped with a filter wheel that can accommodate 6 filters to carry out measurements in different wavelengths. To provide patterned illumination of the array a mask of arbitrary transmission pattern (e.g. pinhole array, mask blocking blocking the light at the array failed open shutters, etc.) can be placed at the source in the conjugate plane with the microshutter array.

The simulator is mechanically attached to the functional cryostat where the microshutter array is mounted for functional and optcal testing. The beam passes through the cryostat windows (both windows are AR coated and tilted to reduce ghosting) passes through the microshutter array comes out through the window on the other side of the dewar where imaging Offner relay forms an image of the microshutter array on the image sensor. In case of the infrared testing the CCD camera is removed and replaced with the IR camera.

Our visible wavelength measurements are carried out at 633nm wavelength using a filter with a 10 nm bandwidth. Since the system should be capable of measuring several orders of magnitude brightness dynamic range, we employ an assortment of neutral density filters. The current detector in use is an Apogee U16M 16 bit camera that provides high signal to noise ratio measurements in the visible light from 300 nm to 1000nm. This CCD camera is equipped with a large format Kodak KAF-16801E 4096 x 4096 pixel enhanced response full-frame CCD image sensor. The physical size of that chip is close to the size of the microshutter array that allows imaging of the whole microshutter array onto the image sensor with only small demagnification, about 0.9. Infrared camera employes a legacy InSb 256 x 256 Spitzer IRCAM detector. The IR detector image covers about 1/3 of the microshutter array image on linear scale. 9 images are acquired to cover the full microshutter array by mosaicing.

Since the microshutter arrays are designed and built to provide high contrast ratio we are dealing with very low light level fluxes ($10^{-4} - 10^{-5}$ of the incoming flux). This required significant efforts to be applied to reduce the system scattered light. This is very important for an unbiased contrast measurement, especially on good arrays that provide very high contrast. We have been able to reduce the amount of the scattered light (on completely closed array) to the level of a few times 10^{-5}. That allows a comfortable margin to measure the *NIRSpec* goal contrast value of 10^4 and even much higher contrast.

The arrays are not perfect and there are always can be shutters that are failed open, i.e. broken or stuck open to the walls even when all the shutters are supposed to be in closed position. On the flight arrays these failed open shutters are patched with special small size (typically 3x3 shutters) pieces of silicon wafer coated with Al coating. That turns failed open shutters into failed closed shutters. As one may imaging, the negative impact of the failed closed shutters on the object selection and quality of the observations produced is much smaller than failed open shutters, because at reasonably low numbers of failed closed shutters (a few thousand are allowed by the *NIRSpec* requirements) there will be no spectra contamination of the selected objects, whereas each failed open shutter will most likely make spectrum of any object along its row unusable. Therefore the flight arrays at the beginning of life will have no failed open shutters. In the process of initial testing, before the arrays have gone through a full fabrication, testing and post-fabrication process there often a number of failed open shutters. To remedy the effects of the scattered light produced by these shutters we came with an idea of the source mask that covers the location of the shutters with dark spots. These dark spots are about a millimeter in diameter and cover a slightly larger area than the failed shutter itself allow to reduce the scattered light that passes through the failed open shutter to an acceptable level that does not affect the result of the contrast measurement over the rest of the array. Since the arrays are of high quality and have only a few of the failed open shutters, the area excluded from the contrast measurements by the source mask blocking failed open shutters is only a few per cent of the total array area. After the failed open shutters on the array are plugged, we repeat the contrast measurements without the source mask and can measure the contrast over its full array area.

To characterize the performance of the array we had to develop a special software system that allows to measure transmission of each and every shutter on the array. During the array functionality testing stage the same image acquisition is utilized. It is used however only to detect gross failures, such as completely failed closed of completely failed open shutters. The analysis software measures coordinates of every shutter on the array and stores the results of the measurements in binary format (”open” or ”closed”) in a database for further analysis. The same software is used for optical contrast characterization, but the results stored have measured contrast value for each shutter on the array. This approach proved to be very valuable for verification of possible evolution of performance of the microshutters during the life tests.

4. SUMMARY

Using a novel approach to the microshutter design together with an actuation mechanism and microshutters addressing opened an avenue to creation of efficient large format aperture mask selection device. An extensive program of modeling and testing the mechanical reliability of the microshutters array. These studies demonstrated that the shutter array design provides a robust device that satisfies the *JWST* lifetime requirements.

At the current stage a number of large format arrays has been tested funcitonally, electrically and for life performance and performed according to expectations. We have developed critical facilities that allow us to test miroshutter arrays functionally and optically in the cryogenic conditions. Results of the microshutter array optical tests have demonstrated that they meet and in many cases far exceed the *JWST NIRSpec* requirements.

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